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URBANIZATION EFFECTS ON OVERWINTERING BROOK AND BROWN TROUT: FISH CONDITION AND MOVEMENT

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ABSTRACT

URBANIZATION EFFECTS ON OVERWINTERING BROOK AND BROWN TROUT: FISH CONDITION AND MOVEMENT

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The combined impacts of urbanization and winter conditions on stream ecosystems and their fish communities is an important area of study that has previously been unaddressed. Urbanized streams commonly exhibit low fish richness and are susceptible to species and diversity loss. Additionally, winter is a period of increased mortality for stream fishes due to physiological and environmental changes. To increase winter survival, fish need sufficient energy reserves, access to good winter habitat, and a decreased likelihood for high risk activities. This study assessed the interactive effects of urbanization and wintertime on brook and brown trout condition and movement. Over the course of two winters, two urban and two rural streams in the Upper Peninsula of Michigan were compared for fish condition and movement using electrofishing and telemetry. Significantly higher mean fish condition was seen in the urban streams for both brook and brown trout, in several size classes, during both winters. Higher mean fish condition was also seen during winter 2 for both brook and brown trout, in most size classes. Mean percentage of recaptured fish that showed movement was not significantly different between the urban and rural streams or between winters. This study suggests stream temperature, water velocity, and fragmentation may explain higher fish condition in urban streams.

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CHAPTER 1: LITERATURE REVIEW

URBANIZATION AND AQUATIC SYSTEMS

Urbanized streams typically show altered hydrology, increased nutrient and contaminant loads, and degraded biota (Meyer et al. 2005; Morgan and Cushman 2005; Paul and Meyer 2001; Roy et al. 2005). Human development and disturbances impact watersheds in many ways. Urbanization near watersheds results in increased stormwater inflow, nutrient inputs, point and non-point pollution, sedimentation, surface water drainage, and loss of riparian vegetation (Marquette Township Planning Commission 2002; Paul and Meyer 2001). Nutrient inputs may include increased phosphorus, nitrogen, sodium, potassium, calcium, and magnesium (Paul and Meyer 2001). Lawns and streets were the primary source of phosphorus introduced into urban streams in a study in Madison, Wisconsin (Paul and Meyer 2001). In Toronto, Ontario, elevated sodium chloride levels were the result of winter deicing of local roads (Paul and Meyer 2001). Non-point pollution sources also include increased heavy metal concentrations that are added to urban streams via industrial discharges and vehicle usage. Brake linings contain nickel, chromium, lead, and copper; tires contain zinc, lead, chromium, copper, and nickel; engine parts contain nickel, chromium, and manganese (Paul and Meyer 2001). These metals and many others accumulate on roads and parking lots, eventually making their way into streams. Vehicles also leak petroleum-based compounds into streams. Organic matter within the stream bed and water column has a high binding capacity for heavy metals (Paul and Meyer 2001). Another source of pollution in urban streams is pesticides, including insecticides, herbicides, and fungicides, which are applied around homes, commercial/industrial buildings, lawns, and golf courses. All of these pollution sources stress aquatic organisms and can lead to a switch from sensitive species to generalist species, including altered algal, invertebrate, and fish communities within urbanized streams (Paul and Meyer 2001). Over 128,000 km of rivers in the United States are negatively impacted by urbanization (Paul and Meyer 2001).

AQUATIC WINTER ECOLOGY

Winter is defined as the period of time after spawning has occurred in autumn-spawning fishes when water temperatures are declining and extending through surface ice break up, ending before spawning has occurred in spring-spawning fishes (Cunjak 1996; Brown et al. 2011). Winter in the northern U.S. is a harsh season with variable environmental conditions that results in changing water temperatures, flow rates, and ice conditions which influence the behavior of stream fishes (Brown et al. 2011) and decrease habitat availability (Lund et al. 2003). Generally, streams experience low water temperatures and discharge rates, varied ice conditions, and shortened day length in winter (Huusko et al. 2007). Winter habitat is also affected by groundwater discharge, snowfall, stream size, latitude and elevation (Brown et al. 2011).

Wintertime can be divided into three periods: early winter (freeze-up), mid-winter (stable conditions), and late winter (ice break-up) (Huusko et al. 2007). Freeze-up occurs in late fall and involves cooling water temperatures that reach the freezing point and is marked by the beginning of ice formation. Mid-winter conditions vary from stable, ice – covered larger, low gradient rivers with ice-free openings in riffles to unstable ice formation on small, steep rivers (Huusko et al. 2007). Ice break-up falls between two extremes: thermal break-up and mechanical break-up (Brown et al. 2011; Huusko et al. 2007). Thermal break-up occurs when solar radiation melts ice, which does not affect water levels. Mechanical break-up occurs when stream discharge increases and breaks up ice, which can scour stream beds (Brown et al. 2011; Huusko et al. 2007) and destroy vegetation (Brown et al. 2001). In general, ice break-up results in habitat changes including altered river channels, movement of islands and gravel beds, and destruction of vegetation and woody debris (Brown et al. 2011).

Forms of ice in rivers includes surface ice, frazil ice, anchor ice, and hanging dams. Surface ice begins forming in early winter along stream banks, with thin, "skim" ice forming in low velocity areas (Huusko et al. 2007). Low gradient streams may develop ice until streams are completely covered while high gradient streams and reaches dominated by riffles and rapids may have fluctuating ice cover (Huusko et al. 2007). Some streams may not freeze over due to warm water influx, groundwater input, or frictional heat developing in rapids (Huusko et al. 2007). Frazil ice is formed when water temperatures drop below 0° C (super-cooled water) and ice crystals formed at the surface are mixed into the water column and grow in size (Brown et al. 1993; Huusko et al. 2007). Frazil ice can affect the respiratory system of trout by plugging gill rakers and abrading tissue (Brown et al. 1993). Anchor ice is formed when frazil ice crystals stick to submerged objects and are deposited on the stream bottom (Brown et al. 1993, 2011), usually in turbulent, shallow stream reaches with rough substrate (Huusko et al. 2007). Typically, frazil ice and anchor ice formation occurs at night (Huusko et al. 2007). Both can force fish movements, which are energetically costly, and may cause mortality (Brown et al. 2000, 2011). Anchor ice can accumulate in riffles and form ice dams which can block water discharge and cause fluctuating water levels (Brown et al. 1993, 2000, 2011; Huusko et al. 2007). Frazil ice can be transported downstream and be deposited under ice cover in areas with low water velocity (like pools) to form hanging dams (Brown et al. 2000, 2011). Hanging dams can increase water velocity and level upstream through channel occlusion, particularly in pools that are important overwintering habitat for salmonids, and decrease water levels downstream (Brown et al. 2001, 2011). Hanging dams can persist for months and make overwintering habitat unusable for an entire season (Brown et al. 2000) or they may be short lived and cause periodic spates downstream. Ice accumulation in pools reduces winter habitat space by changing the physical environmental conditions of this important habitat (Brown et al. 2000; Cunjak 1996). Streams with frequent frazil and anchor ice are considered unstable environments and salmonids will often move out of these areas (Brown et al. 1993, 2000; Huusko et al. 2007).

BROOK AND BROWN TROUT BIOLOGY

The family Salmonidae consists of trouts and their allies (salmon, whitefish and char) including seven genera and 40 species found in North America (Robins et al. 1999); many of these species are important food sources or sport fisheries. These fishes are primarily freshwater species, although many are anadromous, and all spawn in freshwater. They are recognized by their lack of fin spines, and the presence of a single dorsal fin and an adipose fin (Robins et al. 1999).

Brook trout (*Salvelinus fontinalis*) are grouped in the genus *Salvelinus* with lake trout (*S. namaycush*), bull trout (*S. confluentus*), Arctic char (*S.alpinus*), and Dolly Varden (*S. malma*); all are known as char (Behnke 2002). Brook, lake, and bull trout are exclusively native to North America. These fishes differ from *Salmo* species by their lack of black spots (Behnke 2002).

Brown trout (*Salmo trutta*) and Atlantic salmon (*S. salar*) are the only two species in the genus *Salmo* found in North America (Behnke 2002). They are morphologically and anatomically similar, but their life history traits and behavior vary (Behnke 2002).

Distribution

Brook trout

Brook trout are native to eastern Canada from the Atlantic drainages of Newfoundland south through the Great Lakes and headwater tributaries of the Mississippi River into the headwaters of the Chattahoochee River in northern Georgia (Behnke 2002; Bosanko 2007); this is *Salvelinus'* most southern natural distribution (Behnke 2002). They have been introduced, and are self-sustaining, in the western United States and Canada, Eurasia, Africa, New Zealand, and Central and South America (Bosanko 2007).

Brown trout

Brown trout are native to Eurasia from northern Iceland eastward to the Kola and Kanin Peninsulas in northern Siberia, southward throughout Europe to the Mediterranean basin and eastward into the Middle East (Behnke 2002). In 1883, eggs were transported from Germany, and later from other European countries, and reared in New York and Michigan hatcheries. Stocking began in 1884 (Behnke 2002) for sport fishing (Helfman et al. 2009). Currently, there are self-sustaining populations found in forty of the forty-eight contiguous states, in southern Canada, and in Newfoundland, which is their northern most distribution. Brown trout have also been successfully introduced in New Zealand, Australia, South America, Southeast Asia, and mountain streams in Africa (Behnke 2002).

Habitat

Brook trout

Compared with other char, brook trout are the least specialized in habitat preference and will use habitats ranging from small creeks to large rivers, beaver ponds, and small to large lakes (Behnke 2002). They survive best in temperatures between 5 and 20° C; optimal temperature for growth and spawning falls in the middle of this temperature range and is size dependent (Power 1980). Minimum oxygen content of water tolerated is 5 ppm (Becker 1983). They have disappeared from parts of their southern range for a variety of reasons, including land use practices that have increased water temperatures and destroyed habitat (Power 1980). Coaster brook trout (coasters) spend part of their life cycle in Lake Superior. Populations of coasters are found in the Nipigon River system, in bays and streams around Isle Royale, in the Salmon Trout River (Bronte et al. 2003), and in streams in Pictured Rocks National Lakeshore (Kusnierz et al. 2009).   Another migratory brook trout form is the salter, which will overwinter in salt water in Atlantic drainages. Associated fish species commonly found with brook trout include sculpin (*Cottus* spp.), white sucker (*Catostomus commersoni*), creek chub (*Semolitus atromaculatus*), pearl dace (*Margariscus margarita*), brook stickleback (*Culaea inconstans*), and brown trout (Becker 1983).

Brown trout

Brown trout also prefer clear, cold streams and shallow areas of lakes and also may spend part of their life cycle in the ocean (Behnke 2002; Bosanko 2007). Optimal temperature range for growth is 13-18° C (Behnke 2002). Minimum oxygen content of water tolerated is also 5 ppm (Becker 1983). In winter, they utilize large substrate for cover (Huusko et al. 2007). Typically, summer habitat for brook and brown trout is in pools (Cunjak and Power 1986). In a study by Brown et al. (2001), brown trout remained relatively stationary during three winters; movement downstream and into runs occurred during one winter of high water discharge. Associated fish species include blacknose dace (*Rhinicthys atratulus*), mottled sculpin (*Cottus bairdii*), white sucker, creek chub, common shiner (*Luxius cornutus*), bluntnose minnow (*Pimephales notatus)*, northern brook lamprey (*Ichthyomyzon fossor*), and American brook lamprey (*Lampetra appendix*) (Becker 1983).

Behavior

Brook Trout

Brook trout activities are determined by length of day, time of day, and season; they tend to remain inactive at dark and during full sun and will search for food in the early morning and late afternoon, otherwise remaining in protected areas (Becker 1983). They are a solitary fish that can be either sedentary or mobile, migrating between overwintering, feeding, and spawning habitat (Power 1980). Larger fish may move to lakes and oceans until spawning season. In the West, brook trout pose threats to native cutthroat and bull trout (Becker 1983; Behnke 2002).

Redd superimposition is a common occurrence among female salmonids. In a study by Essington et al. (1998), 19 of 36 (53%) brook trout and 37 of 108 (34%) brown trout superimposed redds. This was not significantly correlated with female abundance, habitat availability, or spawner density (females per square meter of habitat), although a correlation has been found in other studies (Beard and Carline 1991; Curry and Noakes 1995). Essington et al. (1998) hypothesized that reusing redd sites made it easier to excavate (reducing energetic costs), resulted in a reduction in sediment (increasing embryo survival), and destroyed competitors eggs (enhancing survival of offspring).

Brown Trout

Brown trout are voracious predators that have decimated native trout populations in their introduced areas, including brook trout in the Great Lakes and East coast and cutthroat trout in the West (Behnke 2002; Helfman et al. 2009; Johnson 2008). Interspecific competition is expected to be high among species with similar life history traits that did not coevolve (Fausch and White 1986). They have been shown to displace brook trout into less favorable stream habitats (Cunjak and Power 1986; Fausch and White 1981), but the opposite has been shown in a laboratory experiment by Fausch and White (1986). More favorable habitats include positions in slow moving water to minimize energy expenditure, but near faster currents bringing more food over time (Fausch and White 1981). In co-inhabited streams, brook trout tend to inhabit upper stream reaches to reduce niche overlap while brown trout are more abundant downstream (Fausch and White 1981). As drifting prey is reduced (in winter) salmonid aggression and territory size increases (Fausch and White 1981). In a brown trout removal study by Fausch and White (1981), brook trout moved to more favorable resting habitats with reduced light but kept the same feeding positions, likely due to visibility of drift organisms. This suggests that resting positions were scarce and feeding positions were plentiful. Habitat preference has been shown to increase territorial defense in brown trout in a lab setting, particularly at low population densities (Johnsson et al. 2000).

Growth and Feeding

Brook trout

Alevins hatch in late winter or early spring (Becker 1983; Helfman et al. 2009) and remain on redds until the yolk sac is absorbed (Becker 1983). They become free swimming around 2.0 cm in length (Becker 1983). Fry 2.0 - 2.5 cm long have a crustacean diet consisting of ostracods, copepods, and cladocerans. They begin feeding on insect larvae and terrestrial insects at 2.5 – 3.8 cm, later switching to small fish. Worms, leeches, spiders, mollusks, frogs, salamanders, fish fry and eggs, crustaceans, insects, and small mammals make up the adult brook trout diet. Male brook trout grow larger than females (Becker 1983). Optimum feeding temperature is 18° C, during low light intensity (Becker 1983). Northern pike (*Esox lucius*), piscivorous birds, including kingfishers, common loons (*Gavia immer*), mergansers (*Mergus* spp.), cormorants, and great blue herons (*Ardea herodias*), as well as river otters (*Lontra canadensis*), snapping turtles (*Chelydra serpentine*), and water snakes (Becker 1983) are their major predators.

Brown trout

Brown trout are opportunistic feeders and have a diet similar to brook trout (Behnke 2002). The brown trout eye is better adapted for dim light due to extra rod cells in their retina (Behnke 2002) and they will feed at night (Behnke 2002; Olsen and

Vollestad 2001), even during the winter months (Heggens et al. 1993).   When inhabiting streams with other salmonids (including brook trout), brown trout have been found to feed on drift at the surface while brook trout feed on bottom dwelling organisms (Behnke 2002). Brown trout feed on leeches, snails, crayfish, mayfly nymphs, and zooplankton (Becker 1983). Smaller fish feed heavily on aquatic and terrestrial insects and switch to a crayfish and fish diet with growth (Becker 1983). Fish species consumed include trout, sculpins, minnows, darters, and lampreys (Becker 1983). Major predators include otters, water snakes, and piscivorous birds (Becker 1983).

WINTER AND SALMONIDS

Survival

Most recent overwinter studies performed on salmonids have been performed on small streams and rivers without ice cover due to easier access and visibility compared to larger systems (Huusko et al. 2007). Wintertime is a period of increased mortality for salmonids due to physiological and environmental changes. To optimize survival, fishes need sufficient energy reserves, access to good winter habitat, and the ability to avoid high risk activities (Huusko et al. 2007). Survival rates vary among rivers, winter months, years, and populations (Hutchings 1994; Huusko et al. 2007; Lund et al. 2003) and are influenced by age and size at maturity (Hutchings 1994). Atypically, estimated monthly survival probability for brown trout was shown to be higher during the winter than during the summer in a study by Olsen and Vollestad (2001). Variation in survival has been substantial in brook (35-73%) and brown trout (15-84%) during their first winter (Huusko et al. 2007). Early winter acclimatization costs affected these fish's survival abilities through long winters (Huusko et al. 2007). Studies have supported size-dependent survival; larger fishes are more able to avoid predators, to resist starvation, and to tolerate physical and physiological changes (‘big is better’ hypothesis), although no evidence for this hypothesis was found in a juvenile brown trout study by Lund et al. (2003). Salmonid eggs and juveniles appear to experience the highest winter mortalities (Huusko et al. 2007). Ice formation, ice break-up, and increased water velocity can disturb gravel which may impact eggs by washing them out, abrading them, and leaving them exposed to desiccation and freezing (Brown et al. 1993; Huusko et al. 2007). A positive relationship has been shown between fish size and winter survival of young-of-the-year brook trout and other salmonids, but has not been demonstrated in other studies, leading to the idea of the importance of energy stores rather than size (Huusko et al. 2007). Predation is a source of mortality in winter, especially from piscivorous mammals and birds, and may explain why many juvenile salmonids become nocturnal in winter (Huusko et al. 2007).

Physiological Changes

An overwintering fish’s primary concern is to minimize energy expenditure, while maximizing protection; therefore salmonids tend to decrease movement, aggression, and feeding, especially during daytime (Brown et al. 2011; Heggens et al. 1993; Huusko et al. 2007). Metabolic processes decrease so the ability to swim, feed, defend habitat positions, and avoid predators declines (Brown et al. 2011). Overwintering salmonids are generally opportunistic feeders that consume drift and benthic food sources (Cunjak et al. 1987; Huusko et al. 2007) whose densities are lower in winter (Brown et al. 2011). Cold water temperatures depress metabolic rates in fish and can prolong their survival without food (Brown et al. 2011). Decreased feeding can lead to a metabolic deficit due to unmet energetic needs and a depletion of fat, protein, and glycogen reserves (Brown et al. 2011; Huusko et al. 2007). Depletion of fat reserves and weight loss throughout winter has been observed in salmonids (Heggenes et al. 1993; Hutchings 1994), including brown trout (Huusko et al. 2007) and brook trout (Cunjak et al. 1987). This decline was shown in immature and post-spawn brook trout in a study by Cunjak et al. (1987) and was thought to be related to their inability to assimilate and digest more food, rather than low food abundance. Brook and brown trout have been shown to have their lowest lipid levels in winter, with levels being depleted the fastest in early winter (Cunjak 1988). Cunjak (1988) also noted that brown trout and immature brook trout had a second period of lipid depletion in late winter. In a brown trout study by Berg and Bremset (1998), reduction in fat content from September to April ranged from 50-65%, protein content reduction ranged from 6-7%, and fat and protein energy content reduction was 28%. In a study by Griffith and Smith (1993), only 61-66% of overwintering juvenile brown trout emerged at night to feed (Cunjak 1996). Other physiological changes, including cellular and tissue changes, buoyancy reduction, and sensitivity to light occur in winter (Huusko et al. 2007). These limitations result in reduced ability to survive in forced swimming events due to habitat changes from ice events and predation (Brown et al. 2011).

Habitat shifts

With decreasing temperatures (~3° to 6° C), increasing water discharge, and decreasing day length, stream fishes commonly migrate to low velocity overwintering habitat with suitable cover to conserve energy and avoid predators (Cunjak 1996; Heggens et al. 1993; Huusko et al. 2007). Utilizing habitat without cover has also been observed (Brown et al. 1993). Energy minimization has been noted in brook and brown trout in a study by Cunjak and Power (1986). Typical movement patterns involve migration downstream (Cunjak and Power 1986), sometimes upstream, or into and out of tributaries (Huusko et al. 2007). Brown trout may move from their summer habitat upstream to overwinter in slower, deeper water (Cunjak 1996). In a Wyoming study, brook trout were found to stay in the same areas all winter after moving into overwintering habitat (low velocity and deep beaver ponds or pools) (Chisholm et al. 1987). Distance travelled varied with ice conditions, discharge, and fish size; fish were more mobile in more unstable conditions (Huusko et al. 2007; Lund et al. 2003). Habitat type selected was species and size dependent with smaller fish inhabiting crevices in the substrate and larger fishes inhabiting slow velocity areas (Huusko et al. 2007). Slow velocity habitats used by salmonids include pools, swamps, side channels and backwaters, beaver ponds, and tributaries (Brown et al. 2001; Huusko et al. 2007). Deep pools and beaver ponds are widely considered stable overwintering habitats (Brown et al. 2011; Cunjak 1996). Groundwater input can also provide stable overwintering habitats (Brown et al. 1993, 2000; Cunjak and Power 1986), but can contribute to unstable conditions downstream (Brown et al. 2000, 2011). Brook trout have been noted to avoid pools more than 250 m downstream of groundwater input due to unstable conditions (Brown et al. 2011). In a study by Brown et al. (1993), 77% of radio tagged cutthroat trout (*Oncorhynchus clarki*) overwintered in areas influenced by groundwater and the other 23% overwintered in pools free of frazil ice and covered with surface ice.

Behavior

Stream fishes use different strategies for winter survival, depending on species, age, and habitat availability (Cunjak 1996). Typically juvenile salmonids, including brown trout, become nocturnal in winter (Berg and Bremset 1998; Heggens et al. 1993; Huusko et al. 2007; Johnson and Douglass 2009; Kaspersson and Hojesjo 2009; Olsen and Vollestad 2001). This is thought to be influenced by temperature, light intensity, social status, age, ice conditions, predator avoidance, and geographic variation (Huusko et al. 2007). Salmonids have been shown to be on or close to the stream bottom at night (Heggens et al. 1993; Huusko et al. 2007). Depending on fish size, smaller salmonids, including brook and brown trout, hide under coarse substrate, large woody debris, vegetation, undercut banks, and ice (Brown et al. 2011; Cunjak 1996; Heggens et al. 1993; Huusko et al. 2007) while larger fish overwinter in deep pools (Cunjak 1996; Heggens et al. 1993). Competition between brown trout and Alpine bullhead (*Cottus poecilopus*) for shelter under rocks and logs has been observed (Olsen and Vollestad 2001). The strategy of seeking shelter during winter months may minimize energy expenditure and reduce predation mortality (Lund et al. 2003). Groundwater input attracts salmonids, including brook and brown trout, during winter (Brown et al. 2000; Cunjak 1996; Huusko et al. 2007). Brook trout prefer close proximity to groundwater sources while brown trout prefer being slightly downstream of input (Cunjak 1996). Groundwater inputs and forced movement from frazil and anchor ice can result in aggregations of fishes (Huusko et al. 2007), particularly adult fishes (Brown et al. 2011). In a study by Cunjak and Power (1986), 86% of the brook and brown trout observed (via snorkeling) were in aggregations; eighteen of the nineteen aggregations were located near groundwater discharge. Aggregations are likely an effect of limited habitat availability and reduced predation risk (Brown et al. 2011) and are good indicators of groundwater discharge, due to its relatively warmer temperature (Cunjak 1996).

Effects of Climate Change

Mean global surface temperatures have increased by 0.3 - 0.6° C in the past century and are expected to increase another 2.0° - 5.8° C in this century (Heino et al. 2009; Perkins et al. 2010; Sharma et al. 2007; Tonn 1990). The effects of this warming will not be evenly distributed; the high latitudes and altitudes are expected to warm the fastest (Heino et al. 2009; Perkins et al. 2010) and be affected the greatest due to low species richness, diversity, slow generation times, more species being at their thermal tolerance, and shrinking and increasingly fragmented habitats (Perkins et al. 2010). Warmer air temperatures will likely result in higher water temperatures and reduced stream flow (Moore et al. 1997; Schindler 1997). This will have many indirect impacts on fish populations around the world, including shifts in thermal tolerance, reduced winter ice cover, longer ice-free periods, and altered stream flow patterns (Heino et al. 2009; Rahel et al. 2008; Rahel and Olden 2008; Tonn 1990). Groundwater temperatures are also expected to increase; this could drastically reduce the range of brook trout and other cold water species (Ficke et al. 2007). Groundwater quantity may also be reduced (Schindler 1997). A series of studies at the Experimental Lakes Area in northern Ontario, in areas of the north eastern U.S., and in Alaska have shown decreasing winter precipitation, earlier ice break-up, and earlier spring snowmelt due to climate change; this appears to cause lower and earlier spring flows (Schindler 1997). Land use within watersheds will also have indirect effects on fishes; riparian habitat is essential to reduce the effects of climate change. Connectivity in streams will be important to insure fish are able to move when temperatures exceed their thermal tolerance levels (possibly upstream in rivers/tributaries near groundwater input). Nelson et al. (2009) developed a model to understand the combined effects of urbanization and climate change on stream fishes in the Chesapeake Bay watershed and found that 50-75% of the fishes would be negatively stressed by their nine future scenarios, with most being affected by climate change. The addition of increased urbanization resulted in even more stressed species being affected, particularly resulting in decreased adult growth (Nelson et al. 2009).

Water temperature is a critical factor in the determination of fish distributions since most fishes (~ 99%) are ectotherms and are directly influenced by the temperature of their environment (Perkins et al. 2010; Tonn 1990). Ectothermic fishes have temperatures they tolerate and optimal temperatures for growth (Hill and Magnuson 1990; Magnuson et al. 1990; Perkins et al. 2010; Rahel et al. 2008; Rahel and Olden 2008; Tonn 1990), therefore, climate change may affect individuals by altering physiological functions including metabolism, behavior, development and growth, food consumption, and reproductive success (Ficke et al. 2007; Magnuson et al. 1990; Perkins et al. 2010; Sharma et al. 2007; Tonn 1990). Climate change could lead to shifts in fish distribution including extirpating coldwater fishes from their present range and allowing warmwater species to expand northward (Chu et al. 2005). Brook trout populations are predicted to become extirpated or fragmented in much of their natural range due to their cold water needs (Moore et al. 1997; Schindler 2001). A model proposed by Chu et al. (2005) predicts a 49% reduction in brook trout distribution by the year 2050. A study by Meisner (1990) on two southern Ontario streams indicated that a 4.1° C increase in summer temperature would reduce brook trout habitat by 42% and 30%. A 50% loss of distribution is predicted for Rocky Mountain coldwater fishes following a projected 3° C increase in mean July air temperatures (Chu et al. 2005).

The toxicity of common pollutants, including heavy metals, to fishes generally increases at higher temperatures, possibly due to production of bioactivated free radicals that are more toxic than parent compounds (Ficke et al. 2007). A positive correlation has been shown between temperature and the bioaccumulation of anthropogenic pollutants, thought to be attributed to increased gill ventilation rates in warmer water temperatures (Ficke et al. 2007; Moore et al. 1997; Schindler 1997). Studies have shown an increase in both temperature and toxins to decrease aquatic macroinvertebrate body sizes, due to larger individuals being more sensitive to toxins (Moore et al. 1997).

URBANIZATION AND SALMONIDS

Urbanized streams often exhibit low fish richness and are susceptible to loss of species and diversity from changes in water quality and stream flow. Surrounding land use changes can have immediate effects on fish populations, including a reduction in spawning, feeding, and resting habitat (Morgan and Cushman 2005), as a result of increased storm flows that increase erosion, which alters habitat availability and quality (Roy et al. 2005). Urbanized streams often have barriers (e.g. impoundments and culverts) that fragment and isolate populations. Often there is a shift from sensitive species to generalist species (Roy et al. 2005; Walsh et al. 2005). Altered hydrology, including increased storm flow, can directly affect fishes by washing out eggs, larvae, or young-of-the-year fish, and indirectly affect fishes by increasing sediment, contaminant, and nutrient input into a stream (Roy et al. 2005). Additionally, habitat size and connectivity were suggested to be important determinants of the distribution of Chinook salmon (*Oncorhynchus tshawytscha*) spawning grounds within the Middle Fork Salmon River in central Idaho (Isaak et al. 2007). Fish responses to altered hydrology may vary depending on life histories (Roy et al. 2005). Kemp and Spotila (1997) found a productive population of brown trout and numerous aquatic macroinvertebrates that were indicators of good water quality in nonurbanized sections of Valley Creek (Philadelphia, PA area). In comparison, the urbanized areas contained pollution-tolerant fish species, including creek chub (*Semotilus atromaculatus*) and green sunfish (*Lepomis cyanellus*), and macroinvertebrates. These urbanized sites also contained a few brown trout; they concluded that this was due to stocking that had occurred previously (but had ended 10 years prior). However, this species was dominating the nonurbanized areas, leading to their hypothesis that the fish were naturally producing a viable population in sites with better water quality. Species associated with the urbanized areas either were not found or were less important in the nonurbanized areas. They also noted that Crabby Creek, a small tributary to the Valley Creek system not impacted by urbanization, contained a naturally producing population of brook trout. This was likely due to the colder water temperatures and the mature forest covering the headwaters of the creek. They concluded that stream sites farthest from urbanization were the least impacted and contained more salmonid and macroinvertebrate species (Kemp and Spotila 1997). Impacts associated with urbanization are generally detrimental to aquatic systems and their fish communities and are well documented in the scientific literature (Kemp and Spotila 1997; Morgan and Cushman 2005; Richards 1976; Roy et al. 2005; Weaver and Garman 1994).

CHAPTER 2: URBANIZATION EFFECTS ON OVERWINTERING BROOK AND BROWN TROUT: FISH CONDITION AND MOVEMENT

CHAPTER SUMMARY

The combined impacts of urbanization and winter conditions on stream ecosystems and their fish communities is an important area of study that has previously been unaddressed. Urbanized streams commonly exhibit low fish richness with susceptibility to species and diversity loss. Additionally, winter is a period of increased mortality for stream fishes due to physiological and environmental changes. This study assessed the interactive effects of urbanization and wintertime on brook (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) condition and movement. Over the course of two winters, two urban and two rural streams in the Upper Peninsula of Michigan, USA, were compared for fish condition, movement, and stream habitat characteristics. Higher mean fish condition was seen in the urban streams for both brook and brown trout, in several size classes, during winter. Higher mean fish condition was also seen during winter 2 for both brook and brown trout, in several size classes. Change in fish condition over winter varied between species. Mean percent of recaptured fish that showed winter movement was not significantly different between the urban and rural streams ($P = 0.253$). Mean monthly stream temperatures were significantly higher in the rural streams during both winters ($P < 0.001$). Habitat comparisons showed a significantly higher mean monthly velocity in all four streams during winter 1. This study suggests stream temperature, water velocity, and fragmentation may explain the higher fish condition in the urban streams.

INTRODUCTION

The purpose of this study was to examine winter effects on brook and brown trout in urbanized and rural streams to make comparisons on fish condition during the winter months when fish are physiologically stressed (Brown et al. 2011; Huusko et al. 2007). Studying the effects of fragmentation, representing decreased connectivity, on fish movement will allow evaluation of potential limits on crucial overwintering movements.

Urbanization poses serious threats to stream ecosystems, but very little research has been conducted on fish communities, with most research occurring only in the last two decades (Kemp and Spotila 1997; Morgan and Cushman 2005; Roy et al. 2005; Walsh et al. 2005; Weaver and Garman 1994). Research has been focused on physical effects, including changes to hydrology, geomorphology, and temperature, and chemical effects, including elevated metals, pesticides, and other organic contaminants (Paul and Meyer 2001). Ecological effects of urbanization are less studied, with most studies looking at invertebrates rather than fishes (Paul and Meyer 2001). Additionally, studies of the effects of habitat fragmentation on biodiversity are focused mainly on landscape ecology with emphasis on terrestrial plants, birds, mammals, and invertebrates (Andren 1997; Fahrig 2003), although researchers are aware of human interactions on the landscape scale as a threat to river ecosystems (Allan 2004). These studies agree that habitat fragmentation increases the degree of isolation between fragments (Allan 2004; Andren 1997).

Fish communities in small (first- to third-order) streams are particularly at risk from the effects of urbanization because they often have low fish richness, making them more susceptible to loss of critical species, and urbanization impacts can have immediate effects on their habitats (Morgan and Cushman 2005). Degraded coldwater streams have seen replacement of sensitive fish and macroinvertebrate species by generalists tolerant of warmwater systems (Walsh et al. 2005). Loss of riparian habitat, wider, shallower streams, and the "heat island effect" associated with urbanization affects stream temperatures (Paul and Meyer 2001). Culverts and ponds impound water and allow suspended sediments to settle to the bottom, decreasing depth, widening streams, and increasing temperatures; culverts, underground diversions, and impoundments can also isolate fish populations (Morgan and Cushman 2005).

Winter in the northern latitudes results in streams with variable environmental conditions that impact stream salmonids and may result in increased mortality (Hutchings 1994; Huusko et al. 2007; Lund et al. 2003). Ice conditions and changing temperatures are physiologically demanding on fish, making wintertime survival difficult (Brown et al. 2011). Ice conditions can force fish movement out of preferred resting habitat while colder temperatures slows metabolic processes, therefore the ability to feed, swim, defend preferred habitat, and avoid predators declines (Brown et al. 2011). Depletion of lipid content, resulting in weight loss, has been observed in several salmonid studies (Cunjak et al. 1987; Heggenes et al. 1993; Hutchings 1994; Huusko et al. 2007). Fish movement is variable during winter, but has been shown to increase in unstable conditions (Huusko et al. 2007; Lund et al. 2003). To optimize survival, fish require access to suitable overwintering habitat with the ability to minimize energy expenditure (Huusko et al. 2007).

The potential problems associated with the interaction of urbanization and wintertime are unknown. Urbanization impacts are associated with poorer water quality and macroinvertebrate communities which may suggest impacted fish communities. Typically, urbanized streams are fragmented watersheds with minimal connectivity. This may restrict fish movement during periods of changing ice conditions when movement is critical and, therefore, increased winter mortality may occur in these systems due to limited overwintering habitat and increased energy expenditure.

There were three objectives for this study. The first objective was to compare brook and brown trout condition between urban and rural reaches and between urban and rural streams, during winter. The second objective was to compare movement of individually tagged brook and brown trout to determine whether habitat fragmentation in the urban streams was influencing movement patterns. The third objective was to compare stream habitat characteristics between urban and rural reaches and between urban and rural streams.

METHODS

This study occurred over two winter seasons: October 2011 – April 2012 (winter 1) and November 2012 – April 2013 (winter 2). Sampling occurred at monthly intervals throughout winter and each sampling event took place over the course of three to five days.

Study Sites

All four study streams were located in Marquette County in Michigan's Upper Peninsula (Figure 2.1). Whetstone Brook and Orianna Creek (Figure 2.2) flow through the city of Marquette, entering Lake Superior directly, and served as the urban streams. Silver Creek and Cedar Creek (Figure 2.3) flow through Chocolay Township and enter the Chocolay River in Harvey (Marquette), Michigan, and served as the rural streams. Study areas in Silver Creek and Cedar Creek had similar topography with maple (*Acer* spp.), mature aspen (*Populus* spp.), Eastern hemlock (*Tsuga canadensis*), and tag alder (*Alnus rugosa*) forests surrounding groundwater fed streams, dominated by sandy substrate. Each stream had three reaches that were sampled; a fourth reach was sampled in each urbanized stream near their headwaters and was considered rural. These fourth reaches had similar topography with maple, mature aspen, Eastern hemlock, Eastern white cedar (*Thuja occidentalis*), and tag alder forests with numerous rock outcroppings surrounding groundwater fed streams, dominated by sandy substrate. All urban reaches were delimited with culverts immediately upstream and downstream of the reach that blocked sunlight penetration to streams (Table 2.1).

The urbanized reaches of Whetstone Brook and Orianna Creek are impacted by culverts, sedimentation, open canopies, unstable water temperatures, habitat degradation, unstable flow, barriers to movement, decreased water quality, pollution, debris dams, stormwater drain pipes, streambank erosion, and water withdrawal (Marquette Township Planning Commission 2002). The rural reaches and streams were located on private property and largely unaffected by urbanization.

Fish Sampling

During the two winter seasons, brook and brown trout were collected by DC backpack electrofishing units (ABP-3 Badger model, ETS, Madison, WI) with a current output around 250 volts (dependent on fish response to the electrical current). Electrofishing (single pass) occurred in early November, January, and March to capture/recapture marked individuals and measure lengths and weights for all salmonids. Shocking time and distance were recorded for each reach. Fish (>100mm) were surgically implanted with 23mm PIT (passive integrated transponder, Oregon RFID, Portland, OR) tags in October / November 2011, January 2012, and November 2012 (Table 2.2). Tags were inserted into the peritoneal cavity after making a small, longitudinally oriented (~5mm) incision into the body wall lateral and slightly posterior to the pectoral fin with a scalpel blade. Fish were not under anesthesia for this study.

Fish condition was calculated using Fulton's Condition Factor (K) which uses fish mass and length to indicate level of energy stores in a fish's body, using the equation,

$$K = 100{,}000*(M/L^3)$$

where K = Fulton's condition factor, M = body mass (g), and L = body length (mm).

Fish Movement

Brook and brown trout locations were determined using a portable backpack PIT tag reader (wand; HDX long range reader, Oregon RFID, Portland, OR) and electrofishing. Tagged fishes were located in opposite months from electrofishing efforts, occurring in early December, February, and April. I located marked individuals by walking upstream and moving the wand throughout the channel, including undercut banks, deep holes, and debris piles. During wanding, the entire study site was surveyed unless snow and/or ice cover prohibited efforts (inability to move throughout the channel or inadequate tag reader range). Typical wanding range was one meter. Locations of fishes from either wanding or electrofishing allowed me to determine whether individuals moved between reaches or remained in their original locations. Undetected tags were not included in this analysis.

Habitat

Temperature

In December 2011, iButton temperature loggers (Thermochron DS1921G-F5 iButton, Maxim Integrated, San Jose, CA) were placed in each reach to record hourly water temperature. Locations were chosen to be easily accessible during winter, with loggers placed mid-channel. They were housed in plastic vials (sealed with silicone) within electrical boxes and secured to rebar stakes. Data was recorded until April 2013; however, several loggers failed and were replaced during this study, resulting in minor data gaps (mostly in summer data with 1-2 month gaps).

The mean seasonal temperature and seasonal range in temperature (max. temp - min. temp) were calculated for each stream reach for each winter (December to early April). Additionally, a mean monthly temperature was calculated for each stream reach for December through March of each winter.

Stream characteristics

Water velocity (Flo-Mate model 2000 portable flowmeter, Marsh-McBirney, Inc., Loveland, CO) and depth was recorded (unless snow cover precluded it) once monthly, during both winters, upstream of the first riffle in each reach. A mean seasonal velocity, mean seasonal depth, change in velocity (max. velocity - min. velocity), and change in depth value were calculated for each stream reach for each winter.

In October 2012, habitat data was collected in each stream reach following the Michigan Department of Natural Resources (MDNR) Stream Status & Trends protocol (Wills et al. 2006). Random transects were placed along each stream reach. Data collected at each transect included predominant stream feature (pool, riffle, or run), riparian vegetative/land use class, streambank vegetative stability class, and depth, dominant substrate, % woody debris, and % rooted vegetation at five distances (20, 40, 60, 80%, thalweg) across the transect. One water velocity measurement (m/s) per reach was also measured upstream of the first riffle in the reach.

Predominant stream feature was classified as a pool, riffle, or run (Wills et al. 2006). Pools were characterized as having deeper than average maximum depths, with no obvious surface turbulence or broken water and slow water velocities. Riffles were characterized as having shallower than average maximum depths, with obvious surface turbulence and faster than average water velocity. Runs were characterized as having moderate maximum depths, with little or no surface turbulence and a smooth water surface. Depth (cm) was determined at 20, 40, 60, and 80% of stream width and at the thalweg. Dominant substrate was classified as clay, detritus/silt, sand, gravel <6.4 cm, small cobble 6.5 – 12.7 cm, large cobble 12.8 – 25.4 cm, boulder >25.5 cm, wood, bedrock or dry land. For this study, small and large cobble were grouped together as 'cobble'. A 0.3 m diameter circle, at each of the five transect increments, was visually scanned to measure large woody debris (>15.2 cm in diameter and >15.2 cm long; 10% increments) and rooted vegetation (10% increments). Dominant riparian vegetation

(>50%) within 9.1 m from the water's edge and 9.1 m upstream and 9.1 m downstream of the transect was recorded on each stream bank. Riparian vegetation classes (land use) were classified as yard/lawn, industrial/commercial, residential, grassland/field, tag alder, small coniferous trees (up to 15.2 cm diameter at breast height (dbh)), large coniferous trees (>15.2 cm dbh), small deciduous trees (up to 15.2 cm dbh), or large deciduous trees (>15.2 cm dbh). For this study, yard/lawn, residential, and grassland/field were grouped together and classified as 'residential'. All coniferous and deciduous trees were grouped and classified as 'forest'. Streambank vegetative stability was recorded on each bank as good (<25% of streambank was bare soil), fair (25-50% of streambank was bare soil), poor (50-75% of streambank was bare soil), or very poor (>75% of streambank was bare soil) (Wills et al. 2006).

Dominant habitat type, dominant substrate class, dominant riparian/land use class, mean depth, % of woody debris, % of rooted vegetation, and stability class were defined for each stream reach, first at the transect level and then at the reach level.

Statistical Analysis

All analyses on fish condition were tested using a t-test, one-way ANOVA, or multiple linear regression. When normality failed, a Mann-Whitney rank sum test or Kruskal-Wallis ANOVA on ranks were used. In all analyses, alpha was set to 0.05.

Due to differences in allometric growth seen in fish maturation (Richter et al. 2000), brook and brown trout condition was analyzed using different size classes. Brook trout condition was analyzed for sub-100 mm and 100+ mm fish while brown trout condition was analyzed for sub-100 mm, 101-199 mm, and 200+ mm fish (Figure 2.4).

T-tests were used to compare means in fish condition for all size classes of brook and brown trout between winters. ANOVA was used to compare mean fish condition factor for all size classes of brook and brown trout among the three electrofishing sampling months. If significance was found between the two winters, then the months were analyzed separately in regards to year; if no significance was found, the months were combined to include both winters (e.g. January 2012 was combined with January 2013). T-tests were used to compare means in fish condition for all size classes of brook and brown trout between urban and rural reaches (per year, combining the months within the particular year.) T-tests were used to compare means in fish condition for all size classes of brook and brown trout between urban and rural streams, excluding the fourth rural reach within the urban streams (per year, combining the months within the particular year.)

A multiple linear regression was used to predict variables that influenced the change in fish condition per day (ΔK) over three sub-winter intervals: November - January, January - March, and November - March. The entire winter interval, November - March was analyzed separately from the other two intervals. All variables tested were specific to a particular fish's reach (where captured) and included stream, winter, winter interval, mean seasonal water temperature, change in seasonal temperature, mean seasonal water velocity, change in seasonal water velocity, mean seasonal water depth, change in seasonal water depth, dominant substrate, streambank stability, mean % of woody debris, dominant land use, initial fish size (upon entering winter), total CPUE, and reach isolation index. Reach isolation index was calculated using the equation,

$$RI = ((C + 1) / RL)) * 100$$

where RI = reach isolation, C = sum of the culvert length directly upstream and downstream of each stream reach (meters), and RL = total reach length (directly upstream and downstream, meters). A high reach isolation index (>10) indicated a high level of isolation (fragmentation) while a low index (<1 - 1) indicated a low level of isolation.

For brook trout, variables included in the regression in the entire winter (Nov - Mar) included stream, initial length, average seasonal depth, % of woody debris, and dominant substrate, as well as possible interactions. Dominant substrate and its interactions were removed from the regression model due to high collinearity or high VIF values. Variables tested in November - January and January - March, included year, initial length, % of woody debris, and total CPUE, as well as possible interactions.

For brown trout, variables tested in the entire winter included change in seasonal water depth and total CPUE, as well as all possible interactions, which were removed from the final regression model do to high VIF values. Variables tested in November - January and January - March included year, initial length, change in seasonal water velocity, dominant substrate, and % woody debris, as well as all possible interactions.

T-tests were used to compare ΔK for brook and brown trout between urban and rural streams during the sub-winter intervals: November - January and January - March / November - March (winter intervals January - March and November - March were grouped due to low sample size). When the test of equal variance failed, a Mann-Whitney rank sum test was used.

T-tests were used to compare means in proportion of recaptured fish (overall) between capture/sampling type (electrofishing or wanding), stream type (urban or rural), and winter season (one or two). T-tests were also used to compare means in percentage of recaptured fish that showed movement for capture/sampling type, stream type, and winter season.

All analyses on stream temperature were tested using one-way ANOVA. When normality failed, a Kruskal-Wallis ANOVA on ranks was used. All analyses on stream habitat characteristics were tested using a t-test or one-way ANOVA. When normality failed, a Mann-Whitney rank sum test or Kruskal-Wallis ANOVA on ranks was used. Mean monthly velocity and depth measurements were analyzed using a one-way ANOVA. When normality failed, a Kruskal-Wallis ANOVA on ranks was used.

RESULTS

Fish Condition

Brook trout were only found in two of the urban reaches in Whetstone Brook; therefore, within stream effects were not analyzed for this species within this stream. This stream was dominated by brown trout, particularly large fish with relatively few small fish (<60 mm; Figure 2.5). Historical data has shown brown trout to be present in Orianna Creek (Taft 1992); however, none were found during this study. This stream contained brook trout only, particularly small fish with relatively few large fish (>150 mm; Figure 2.6). Cedar and Silver Creek were inhabited by brook, brown, and rainbow trout (*O. mykiss*), as well as coho salmon (O. *kisutch*; Table 2.3). Both rural streams contained few large brook (>100 mm; Figure 2.6) and brown trout (>130 mm; Figure 2.5); although Cedar Creek had several brown trout >300 mm that entered the stream temporarily to spawn.

Brook Trout

Within Stream Comparisons

In Orianna Creek, comparisons between winter one and winter two showed significantly higher mean fish condition for sub-100 mm brook trout during winter 2 in the urban (U = 7088; n per winter 1 = 109; n per winter 2 = 172; P < 0.001; Figure 2.7) and rural reaches (U = 10313; n per winter 1 = 176; n per winter 2 = 200; P < 0.001). Fish condition was also significantly higher for 100+ mm brook trout during winter 2 in the urban (U = 10194; n per winter 1 = 174; n per winter 2 = 138; P = 0.022) and rural reaches (U = 596.5; n per winter 1 = 67; n per winter 2 = 37; P < 0.001). Comparisons between urban and rural reaches showed significantly higher mean fish condition for sub-100 mm brook trout in the urban reaches during both winter one (U = 6116; n per urban reaches = 109; n per rural reach = 176; P < 0.001) and winter two (U = 14994.5; n per urban reaches = 172; n rural reach = 200; P = 0.033). Mean fish condition was also significantly higher for 100+ mm brook trout in the urban reaches during winter one (U = 2609.5; n per urban reaches = 174; n per rural reach = 67; P < 0.001) and winter two (U = 1974; n per urban reaches = 138; n rural reach = 37; P = 0.035; although the power of the test (0.050) was low).

In Cedar Creek, comparisons between winter one and winter two showed no significant difference in mean fish condition for sub-100 mm (P = 0.545; t = -0.636; df = 7) or 100+ mm brook trout (P = 0.906; t = 0.121; df = 13; Figure 2.7).

In Silver Creek, comparisons between winter one and winter two showed significantly higher mean fish condition during winter two for sub-100 mm brook trout (U = 9543.5; n per winter 1 = 183; n per winter 2 = 140; P < 0.001), but no significance was shown for 100+ mm brook trout (U = 8455.5; n per winter 1 = 107; n per winter 2 = 182; P = 0.062; Figure 2.7).

Between Stream Comparisons

Comparisons between urban and rural streams showed significantly higher mean fish condition in the urban streams for sub-100 mm brook trout during winter one (U = 5696; n per urban streams = 110; n per rural streams = 190; $P < 0.001$) and winter two (U = 6695.5; n per urban streams = 172; n rural streams = 146; $P < 0.001$). Mean fish condition was also significantly higher in the urban streams for 100+ mm brook trout during winter one (U = 7163.5; n per urban streams = 241; n per rural streams = 117; $P < 0.001$) and winter two (U = 4768; n per urban streams = 157; n rural streams = 176; $P < 0.001$; Figure 2.7).

Recaptured brook trout

Comparisons between urban and rural streams showed no significant difference in mean ΔK for either winter interval Nov - Mar (P = 0.353; t = 0.963; df = 13; although the power of the test (0.050) was low) or Nov - Jan / Jan - Mar (P = 0.169; t = 1.421; df = 22; although the power of the test (0.152) was low). Due to the small sample sizes and low power, the trend for larger ΔK seen in the urban streams is suggestive of differences between urban and rural streams (Figure 2.8).

Thirty-nine brook trout were recaptured over the two winter seasons. In the winter intervals Nov - Jan and Jan - Mar (24 total fish; Table 2.4), ΔK was best described by year (p = 0.047, t = 2.137), initial length (p = 0.007, t = -3.025), % woody debris (p = 0.042, t = 2.185), and reach isolation index (p = 0.005, t = 3.221). Total CPUE did not significantly affect ΔK. The final regression model was ΔK = 0.00186 + (0.00116 * Year) - (0.0000352 * Initial Length) + (0.000376 * Wood) + (0.000281 * F) + (0.244 * Total CPUE) with a R^2 value of 0.483 ($P = 0.025$). In the winter interval Nov - Mar (15 total fish), ΔK could not be explained (numerous insignificant regression models, likely due to low sample size); however, Whetstone Brook ($p = 0.046$, $t = 2.316$) and initial length ($p = 0.039$, $t = -2.416$) were the only significant variables while Orianna Creek, mean seasonal water depth, and % woody debris did not significantly affect ΔK. The final regression model was ΔK = 0.00448 + (0.00159 * Stream 1) + (0.000986 * Stream 2) - (0.0000159 * Initial Length) - (0.00125 * Ave Depth) + (0.0000383 * Wood) with a R^2 value of 0.574 ($P = 0.117$).

Brown Trout

Within Stream Comparisons

In Whetstone Brook, comparisons between winter one and winter two showed significantly higher mean fish condition during winter 2 for sub-100 mm brown trout in the urban ($U = 104504.5$; n per winter 1 = 435; n per winter 2 = 639; $P < 0.001$; Figure 2.9) and rural reaches ($U = 522$; n per winter 1 = 24; n per winter 2 = 91; $P < 0.001$). Mean fish condition was significantly higher during winter 2 for 101-199 mm brown trout in the rural reach ($U = 4763.5$; n per winter 1 = 161; n per winter 2 = 101; $P < 0.001$); although no significant differences were shown in the urban reaches ($U = 76839.5$; n per winter 1 = 198; n per winter 2 = 801; $P = 0.499$) . Mean fish condition was significantly higher during winter 1 for 200+ mm brown trout in the urban reaches ($U = 6538$; n per winter 1 = 167; n per winter 2 = 138; $P < 0.001$); although no significance was shown in the rural reach (P = 0.143; t = -1.684; df = 6; however, the power of the test (0.202) was low). Comparisons between urban and rural reaches showed significantly higher mean fish condition for sub-100 mm brown trout in the urban reaches during winter one (U = 1587; n per urban reaches = 435; n per rural reach = 24; P < 0.001) and winter two (U = 13363.5; n per urban reaches = 639; n rural reach = 91; P < 0.001). Mean fish condition was significantly higher for 101-199 mm brown trout in the urban reaches during winter one (U = 3559.5; n per urban reaches = 198; n per rural reach = 161; P < 0.001) and winter two (U = 22893; n per urban reaches = 801; n rural reach = 101; P < 0.001). Mean fish condition was also significantly higher for 200+ mm brown trout in the urban reaches during winter one (U = 173; n per urban reaches = 167; n per rural reach = 6; P = 0.007), although not during winter two (U = 62; n per urban reaches = 138; n rural reach = 2; P = 0.185).

In Cedar Creek, comparisons between winter one and winter two showed significantly higher mean fish condition during winter two for sub-100 mm (U = 1968; n per winter 1 = 94; n per winter 2 = 89; P < 0.001) and 101-199 mm brown trout (U = 15462; n per winter 1 = 202; n per winter 2 = 175; P = 0.036). No significant difference was shown for 200+ mm brown trout (P = 0.608; t = 0.515; df = 109; although the power of the test (0.050) was low; Figure 2.9).

In Silver Creek, comparisons between winter one and winter two showed significantly higher mean fish condition during winter two for sub-100 mm (U = 3233.5; n per winter 1 = 119; n per winter 2 = 68; P = 0.023) and 101-199 mm brown trout (U = 9744; n per winter 1 = 163; n per winter 2 = 149; P = 0.003). No significant difference was shown for 200+ mm brown trout ($P = 0.748$; $t = 0.326$; $df = 20$; although the power of the test (0.050) was low; Figure 2.9).

Between Stream Comparisons

Comparisons between urban and rural streams showed significantly higher mean fish condition in the urban streams for sub-100 mm brown trout during winter one ($U = 10031.5$; n per urban streams = 435; n per rural streams = 213; $P < 0.001$) and winter two ($U = 20052$; n per urban streams = 639; n rural streams = 157; $P < 0.001$). Mean fish condition was significantly higher in the urban streams for 101-199 mm brown trout during winter one ($U = 13939$; n per urban streams = 198; n per rural streams = 369; $P < 0.001$) and winter two ($U = 68164$; n per urban streams = 802; n rural streams = 326; $P < 0.001$). Mean fish condition was also significantly higher in the urban streams for 200+ mm brown trout during winter one ($U = 3273.5$; n per urban streams = 167; n per rural streams = 60; $P < 0.001$), but not winter two ($P = 0.965$; $t = -0.0438$; $df = 203$; however, the power of the test (0.050) was low; Figure 2.9).

Recaptured brown trout

Comparisons between urban and rural streams showed a significantly higher mean ΔK in the rural streams for both winter intervals Nov - Mar ($P = 0.008$; $t = -2.723$; $df = 65$) and Nov - Jan / Jan - Mar ($U = 1325$; n per urban stream = 66; n per rural stream = 53; $P = 0.024$; Figure 2.8).

One hundred and eighty-six brown trout were recaptured over the two winter seasons. In the winter intervals Nov - Jan and Jan - Mar (119 total fish; Table 2.4), ΔK was best described by change in seasonal water velocity ($P = 0.002$; $t = -3.168$) and %

woody debris ($p < 0.001$, $t = -3.944$). Year, winter interval, initial length, and substrate did not significantly affect ΔK. The final regression model was ΔK = 0.00209 + (0.00127 * Year) + (0.000447 * Winter Interval) - (0.00000510 * Initial Length) - (0.00243 * Change in Seasonal Velocity) - (0.000244 * Dominant Substrate) - (0.0000841 * Woody Debris) with a R^2 value of 0.202 ($P < 0.001$). In the winter interval Nov - Mar (67 total fish), ΔK was best described by change in seasonal water depth ($p = 0.042$, $t = 2.073$). Total CPUE did not significantly affect ΔK. The final regression model was ΔK = 0.000540 + (0.000280 * Change in Seasonal Water Depth) - (0.0331 * Total CPUE) with a R^2 value of 0.0992 ($P = 0.035$).

Fish Movement

Mean proportion of recaptured fish was not significantly different between the urban and rural streams (U = 150; n urban streams = 20; n rural streams = 20; P = 0.180; Figure 2.10) or capture/sampling type (P = 0.084; t = 1.774; df = 38; however, the power of the test (0.282) was low, possibly due to low sample size (n per electrofishing effort = 24; n per wanding effort = 16)). Mean proportion of recaptured fish was not significantly different between winters (U = 144; n per winter 1 = 20; n per winter 2 = 20; P = 0.133).

Mean percentage of recaptured fish that showed movement out of their initial reach was not significantly different between the urban and rural streams (U = 163.5; n urban streams = 20; n rural streams = 20; P = 0.253; Figure 2.11), capture/sampling type (U = 188; n per electrofishing effort = 24; n per wanding effort = 16; P = 0.910), or between winters (U = 194.5; n per winter 1 = 20; n per winter 2 = 20; P = 0.874). Overall fish recapture and movement data is shown in Table 2.5.

Stream Characteristics

Stream Temperature

Within Stream Comparisons

In Whetstone Brook, comparisons between winter one and winter two showed significantly higher mean monthly temperatures during winter one ($P = 0.009$; $df = 1$). Comparisons between urban and rural reaches did not show differences for mean monthly temperatures ($P = 0.605$; $df = 1$). In Orianna Creek, mean monthly temperatures were not significantly different between winters ($P = 0.545$; $df = 1$) or urban and rural reaches ($P = 0.294$; $df = 1$). Mean monthly temperature were not significantly different between winters in Cedar Creek ($P = 0.213$; $df = 1$) or Silver Creek ($F = 2.818$; $P = 0.109$; $df = 1,20$; however, the power of the test (0.237) was low).

Between Stream Comparisons

Comparisons between urban and rural streams showed significantly higher mean monthly stream temperatures in the rural streams during winter one ($P < 0.001$, $df = 1$) and winter two ($F = 47.972$; $P < 0.001$; $df = 1,42$). Comparisons between mean January 2012, July 2012, and January 2013 temperatures showed warmer peak summer temperatures (4°C difference) in the urban streams but colder mid-winter temperatures in these streams (1.5°C difference during winter 1 and 1.3°C difference during winter 2; Figure 2.12).

Habitat Characteristics

Within Stream Comparisons

In Whetstone Brook, comparisons between urban and rural reaches showed a significantly higher reach isolation index ($P < 0.001$; df = 3) in the urban reaches. No difference was shown for mean monthly water velocity ($P = 0.076$; df = 1; Figure 2.13) or mean monthly water depth ($P = 0.756$; df =1; Figure 2.14). Comparisons between winter one and winter two showed significantly higher mean monthly water velocity during winter one ($P < 0.001$; df = 1) but no significance in mean monthly water depth ($P = 0.130$; df = 25).

In Orianna Creek, comparisons between urban and rural reaches showed a significantly higher reach isolation index ($P < 0.001$; df = 3), mean monthly water velocity ($P = 0.019$; df = 1; Figure 2.13) and depth ($P = 0.012$; df =1; Figure 2.14) in the urban reaches. Comparisons between winter one and winter two showed significantly higher mean monthly water velocity ($P < 0.001$; df = 1) and depth ($P = 0.005$; df = 1) during winter one.

In Cedar Creek, comparisons between winter one and winter two showed significantly higher mean monthly water velocity during winter one ($P < 0.001$; df = 1; Figure 2.13) and significantly higher mean water depth during winter two ($P = 0.001$; df = 1; Figure 2.14).

In Silver Creek, comparisons between winter one and winter two showed significantly higher mean monthly water velocity during winter one ($P = 0.001$; df = 1; Figure 2.13) and significantly higher mean water depth during winter two ($P = 0.005$; df = 1; Figure 2.14).

Between Stream Effects

Comparisons between urban and rural streams showed significantly higher % wood ($P = 0.039$; $df = 7$) in the rural streams and a higher reach isolation index ($P < 0.001$; $df = 9$; Table 2.6) in the urban streams. No significant difference between stream types was shown for mean water velocity ($P = 0.096$; $df = 1$; Figure 2.13) or mean water depth ($P = 0.813$; $df = 1$; Figure 2.14) during winter one or winter two (velocity: P = 0.1.000; $df = 1$; depth: $P = 0.741$, $df = 1$).

DISCUSSION

Winter Fish Condition

Impacts associated with urbanization are generally considered detrimental to aquatic systems and their fish communities and are well documented in the scientific literature (Kemp and Spotila 1997; Morgan and Cushman 2005; Richards 1976; Roy et al. 2005; Weaver and Garman 1994). However, the urban / rural stream effect in this study showed that mean fish condition during winter was higher in the urban streams for most size classes of brook and brown trout. Mean monthly winter stream temperatures were higher in the rural streams which may partially explain the higher condition in the urban streams. Warmer stream temperatures would indicate higher metabolic rates in ectothermic fish (Clarke and Johnston 1999), requiring them to expend more energy under otherwise similar conditions, and depleting their lipid content faster, hence lowering fish condition. Most studies addressing urbanization impacts on fish communities show that warmer urban stream temperatures have a negative impact on ecosystems; however, these studies generally take place during the summer months when warmer temperatures in urban streams, resulting from loss of riparian shading, lead to very high metabolic rates and sometimes exceeding thermal tolerances (Nelson and Palmer 2007; Paul and Meyer 2001). This study has shown that colder temperatures are occurring in the urban streams during winter and this may actually be beneficial to fish condition. Temperature data in my study showed the common trend of warmer urban waters in summer, but relatively colder winter temperatures during mid-winter months, demonstrating a greater seasonal change in temperatures in the urban streams. Paul and Meyer (2001) referenced a similar trend during a 1970 study on Long Island, NY, when examining urbanized streams relative to forested streams. This change in thermal profile in urbanized systems is another reason that the effect of urbanization should be examined throughout the annual thermal cycle to more fully understand the effects of development on fishes.

A higher reach isolation index (fragmentation) in the urban streams could also help explain higher condition if isolated populations showed limited / minimal movements and a related decrease in energy expenditure. Both urban streams were ice and snow covered during large portions of both winters (compared to the rural streams which were generally open) possibly protecting the fish from predation and other events that might require movement. Regular snow plowing of parking lots into both urban streams was occurring throughout the two winters. This protective layer may have resulted in minimal forced movement and energy expenditure. Suitable winter habitats for stream salmonids allow fish to minimize energy expenditure and maximize protection from environmental variation and predation (Cunjak 1996; Cunjak and Power 1986). In a winter study by Watz et al. (2013), ice cover benefited juvenile brown trout by reducing stress levels and allowing increased food consumption due to perceived overhead protection from predators. Other studies have shown the importance of ice cover on reduced metabolic rates in salmonids (Finstad 2004; Huusko et al. 2007). Fragmentation combined with a relatively protective ice cover may result in a decreased need and ability to move in the urban streams, although more research will be necessary to evaluate this hypothesis.

In Whetstone Brook, very few small fish (brown trout <60 mm and brook trout <100 mm; Figures 2.5 and 2.6) were present suggesting these small fish may be an important winter food source for the larger brown trout leading to higher condition paired with low recruitment. The rural stream communities contained four species of salmonids, therefore interspecific competition for resources (food, cover, resting habitat) could also result in lower condition, although colder winter temperatures are expected to reduce levels of competition due to lower metabolic rates. Additionally, brook trout are the only salmonids in Orianna Creek, with few large fish (>150 mm) present and competition may be reduced in the stream, resulting in higher condition.

Mean fish condition was higher in the urban reaches of Whetstone Brook and Orianna Creek compared to rural sites within the same streams for most size classes of brook and brown trout. No difference was observed in mean monthly water temperatures; however, a higher reach isolation index in the urban reaches may help explain higher condition due to isolated populations with limited possible movements and less associated energy expenditure. In Orianna Creek, a higher mean monthly depth in the urban reaches was seen and the rural reach provided few apparent deep water habitats during winter, while the urban reaches had numerous pools available. These overwintering pools, combined with ice and snow cover and snow plowing, may have provided suitable habitat to minimize movement and energy expenditure. However, both rural reaches in Orianna Creek and Whetstone Brook also became ice and snow covered during portions of the winter.

The interannual effect in this study revealed higher fish condition during winter 2 for most size classes of brook and brown trout. Habitat comparisons showed a higher mean monthly velocity in all four streams during winter 1; therefore, higher condition during winter 2 may be associated with slower, more stable environments. Cedar and Silver Creeks both had greater water depths during winter 2; only Orianna Creek had higher water depths during winter 1.

Winter Change in Fish Condition

Differences between urban and rural streams showed a higher ΔK for brown trout in the rural streams during all winter intervals, Nov - Mar and Nov - Jan / Jan - Mar, which was likely driven by early winter (Nov - Jan; Figure 2.8) as late winter (Jan - Mar) showed similar changes between urban and rural streams. Although no significant difference was seen in ΔK for brook trout in the urban and rural streams, a consistent trend was observed of higher apparent ΔK in the urban steams with the greatest apparent differences between stream types seen in early winter (Figure 2.8). A decrease in fish condition in early winter as an indicator of stress associated with high acclimatization costs has been shown by Huusko et al. (2007). Thus, although similar patterns in absolute fish condition were shown for brook and brown trout in this study, patterns of change in condition were species specific. These species differences could be related to the difference between native and nonnative species or they may reflect simple species differences regardless of the evolutionary origin of the fish. The higher ΔK in the rural streams for brown trout and the higher ΔK in the urban streams for brook trout suggests brown trout may be more suitable for urban environments than brook trout in our area and that at least some of this difference may be related to the response of these species to winter conditions. This is clearly an area where more research on species responses to winter would contribute to our understanding of the ecological consequences of non-native fish species.

Impacts of environmental variables on ΔK was also species specific as ΔK in brown trout was best described by change in seasonal water velocity, % woody debris (Nov - Jan / Jan - Mar), and change in seasonal water depth (Nov - Mar) while brook trout ΔK was best described by year, % woody debris, reach isolation index, and initial length (Nov - Jan / Jan - Mar). All of these environmental variables were important in this study and suggest that different environmental conditions play a role in driving the change in fish condition over winter within urban and rural environments in different species.

Variability in Urban Effects

The magnitude of urbanization impacts on stream ecosystems differs greatly among locales with human development and disturbances impacting watersheds all around the world. Streams in the Upper Peninsula of Michigan are often considered clean, protected, and in a relatively natural condition; however, there are plenty of streams impacted by obvious things like dams, loss of riparian vegetation, and pollution. The level of urbanization was also not equal in Whetstone Brook and Orianna Creek. In comparison to Whetstone Brook, I found Orianna Creek to be less impacted, with fewer and shorter underground diversions, less riparian vegetation removal, and a viable population of native brook trout. Land use within Orianna Creek was 72% open space/undeveloped land with 1% commercial/industrial use while Whetstone Brook's watershed was comprised of 58% open space/undeveloped land with 13% commercial/industrial use (Marquette Township Planning Commission 2002; see Appendix A). Orianna Creek is a relatively unusual stream where native brook trout dominate an urbanized watershed; therefore, this stream may be important in understanding how to protect brook trout fisheries around the Great Lakes region during climate change and other anthropogenic influences. It also represents a rare local watershed that is dominated by native brook trout that is under threat from continued development and which warrants conservation efforts.

Whetstone Brook was dominated by numerous large brown trout. Brook trout were present in the lower two reaches, although their numbers diminished during this study (Table 2.3). The lack of juvenile recruitment seen during this study (Figure 2.6) also suggests that brook trout may become extirpated from Whetstone Brook in the future. Despite the high fish condition seen in the brown trout, there was a lack of diversity expected in a healthy ecosystem (no other fish inhabit this stream). Additionally, no fish movement occurred in the third urban reach or the rural reach; these fish were functionally isolated populations as a result of culverts and possible fish barriers. Preservation of Whetstone Brook brook trout should be a focus for fisheries managers and city officials; restoring stream connectivity and addressing seasonal temperature changes by enhancing riparian vegetation may be helpful.

Conclusions

The Great Lakes basin is an important freshwater ecosystem that should be monitored and protected for future use. The effects of urbanization, winter, and climate change will all have immediate effects on freshwater fisheries, potentially leading to abrupt ecosystem changes, including extirpations, warming waters, and removal of important riparian vegetation and instream cover. In this study, I identified unexpected impacts on fish condition reflective of both winter and environmental effects linked to urbanization and species-specific differences that may be important for native species conservation. It will be important to continue to investigate changing responses by fish to winter conditions related to human impacts.

Table 2.1. Stream reach locations for Whetstone Brook, Orianna Creek, Cedar Creek and Silver Creek.

Stream	Reach	Start Location	Distance	Lat/Long
Whetstone	1	Grove St. / Seventh St.	580 m	N 46.54025 W 87.70611
	2	Waste Management culvert	287 m	N 46.54423 W 87.41593
	3	Meeske St.	114 m	N 46.54655 W 87.42740
	4	Vandenboom Rd.	250 m	N 46 32.701 W 87 26.278
Orianna	1	Soo Line RR (Shiras Generating Plant)	78 m	N 46.53241 W 87.39462
	2	MQT Federal Credit Union culvert	247 m	N 46.53035 W 87.39735
	3	Division St.	540 m	N 46.52948 W 87.39989
	4	McClellan Ave.	250 m	N 46 31.765 W 87 25.076
Cedar	1	40 m upstream of Cherry Creek Rd.	100 m	N 46.45652 W 87.35731
	2	Private residence #1 (Old Kiln Rd.)	100 m	N 46.45571 W 87.36189
	3	Private residence #2 (Old Kiln Rd.)	100 m	N 46 27.111 W 87 22.225
Silver	1	Silver Creek Rd. (2nd crossing)	250 m	N 46.47988 W 87.38576
	2	Private residence #3 (Deer Run)	250 m	N 46.47666 W 87.38452
	3	Private residence #4 (Silver Creek Rd.)	250 m	N 46 28.358 W 87 23.867

Table 2.2. Number of PIT (passive integrated transponder) tags placed into the urban and rural streams during the 2011 - 2012 and 2012 - 2013 field seasons and the number of brook (BKT) and brown trout (BRN) tagged.

Date	**Stream**	**# of Tags**	**BKT**	**BWN**
Oct/Nov 2011	Whetstone	71	7	64
	Orianna	61	61	0
	Cedar	50	2	48
	Silver	49	22	27
January 2012	Whetstone	50	11	39
	Orianna	19	19	0
	Cedar	51	6	45
	Silver	50	20	30
November 2012	Whetstone	155	4	151
	Orianna	97	97	0
	Cedar	84	0	84
	Silver	57	31	26

Table 2.3. Total fish catch in all 4 streams for the 2011-12 and 2012-13 field seasons. Abbreviations are BKT=brook trout, BWN=brown trout, COHO= coho salmon (*Oncorhynchus kisutch*), and STL=steelhead trout (*O. mykiss*).

Stream/Reach	Oct/Nov 2011	Jan 2012	March 2012	Nov 2012	Jan 2013	March 2013
Whetstone 1	12 BKT 398 BWN	22 BKT 146 BWN	7 BKT 66 BWN	649 BWN	1 BKT 450 BWN	1 BKT 367 BWN
2	13 BKT 24 BWN	9BKT 9 BWN	5 BKT 7 BWN	4 BKT 40 BWN	8 BKT 29 BWN	5 BKT 24 BWN
3	75 BWN	60 BWN	19 BWN	16 BWN	8 BWN	3 BWN
4	145 BWN	38 BWN	7 BWN	87 BWN	71 BWN	37 BWN
Total	**667 FISH**	**284 FISH**	**111 FISH**	**796 FISH**	**567 FISH**	**437 FISH**
Orianna 1	7 BKT	1 BKT	2 BKT	1 BKT	2 BKT	5 BKT
2	81 BKT	0	9 BKT	69 BKT	18 BKT	3 BKT
3	120 BKT	13 BKT	50 BKT	168 BKT	18 BKT	28 BKT
4	171 BKT	51 BKT	22 BKT	162 BKT	39 BKT	37 BKT
Total	**423 FISH**	**79 FISH**	**85 FISH**	**400 FISH**	**77 FISH**	**73 FISH**
Cedar 1	1 BKT 43 BWN 39 COHO	1 BKT 28 BWN 10 COHO 12 STL	40 BWN 6 COHO 2 STL	47 BWN 1 COHO 4 STL	39 BWN 4 COHO 1 STL	30 BWN 2 COHO 4 STL
2	59 BWN 22 COHO 1 STL	4 BKT 51 BWN 8 COHO	2 BKT 37 BWN 1 COHO	58 BWN 2 STL	26 BWN 3 COHO	26 BWN 2 COHO
3	2 BKT 47 BWN 15 COHO	4 BKT 32 BWN 9 COHO	3 BKT 23 BWN 3 COHO	2 BKT 42 BWN 1 STL	2 BKT 26 BWN 1 COHO	5 BKT 29 BWN 1 COHO
Total	**229 FISH**	**213 FISH**	**149 FISH**	**240 FISH**	**102 FISH**	**99 FISH**
Silver 1	14 BKT 52 BWN 17 COHO 8 STL	17 BKT 24 BWN 6 COHO 7 STL	22 BKT 23 BWN 5 COHO 3 STL	24 BKT 30 BWN 4 COHO 8 STL	16 BKT 30 BWN 1 COHO 8 STL	5 BKT 6 BWN 1 STL
2	18 BKT 70 BWN 3 COHO 11 STL	15 BKT 42 BWN 14 COHO	14 BKT 21 BWN 16 COHO 4 STL	37 BKT 52 BWN 1 COHO 9 STL	27 BKT 24 BWN 2 COHO 8 STL	
3	76 BKT 32 BWN 6 COHO 3 STL	52 BKT 31 BWN 4 COHO 2 STL	62 BKT 26 BWN 5 COHO 1 STL	79 BKT 37 BWN 1 COHO 9 STL	81 BKT 33 BWN 2 COHO 6 STL	56 BKT 21 BWN 4 STL
Total	**310 FISH**	**214 FISH**	**230 FISH**	**291 FISH**	**238 FISH**	**93 FISH**

Table 2.4. Number of recaptured fishes during electrofishing efforts for both 2011-12 and 2012-13. Data shows the number of recaps over 3 time periods: November to January, January to March, and November to March.

Winter	Stream	Species	Nov-Jan	Jan-Mar	Nov-Mar
1	Whetstone	BKT	2	2	1
1	Whetstone	BWN	4	3	4
1	Orianna	BKT	4	0	6
1	Cedar	BWN	4	8	8
1	Silver	BKT	3	11	4
1	Silver	BWN	11	8	2
2	Whetstone	BKT	1	1	2
2	Whetstone	BWN	51	11	37
2	Orianna	BKT	1	0	1
2	Cedar	BWN	18	7	13
2	Silver	BKT	7	2	4
2	Silver	BWN	8	0	5

Table 2.5. Overall recapture and movement data for Whetstone Brook (W), Orianna Creek (O), Cedar Creek (C), and Silver Creek (S) during 2011-12 and 2012-13. Table shows total number of tagged fish, recaptured fish, and fish that moved to a new reach other than originally tagged, within each stream and for each month sampled (D=December, J=January, F=February, M=March, A=April). Recapture data from December, February, and April are from the handheld PIT tag reader; recapture data from January and March are from electrofishing.

Stream		Winter 1			Winter 2		
_	Date	# tagged	# recaps	# moved	# tagged	# recaps	# moved
W	D	121	15	0	155	47	1
	J	121	6	0	155	52	0
	F	171	30	0	155	0	0
	M	171	9	0	155	39	1
	A	171	27	0	155	59	1
O	D	80	24	1	97	47	1
	J	80	4	0	97	1	0
	F	99	6	1	97	0	0
	M	99	6	2	97	1	0
	A	99	5	1	97	10	1
C	D	101	13	1	84	42	0
	J	101	4	0	84	18	0
	F	152	26	0	84	23	0
	M	152	14	0	84	10	1
	A	152	13	0	84	22	0
S	D	99	16	0	57	24	1
	J	99	14	0	57	15	0
	F	149	37	0	57	1	0
	M	149	20	1	57	8	1
	A	149	24	0	57	8	0

Table 2.6. Habitat comparisons between urban and rural stream. A significantly higher % wood ($P = 0.039$) was shown in the rural streams. A significantly higher reach isloation index ($P < 0.001$) was shown in the urban streams.

	Urban Streams	Rural Streams
Predominant Stream Feature	11% pools 30% riffles 59% runs	8% riffles 92% runs
Substrate	3% silt 29% sand 50% gravel 18% cobble	88% sand 12% gravel
% Wood	0	6
Reach Isolation Index	111.35 ± 160.78	3.05 ± 3.10
L Bank Riparian Land Use	29% residential 5% industrial/commercial 10% tag alder 56% forest	7% residential 4% tag alder 89% forest
R Bank Riparian Land Use	38% residential 19% industrial/commercial 13% tag alder 30% forest	7% residential 11% tag alder 82% forest

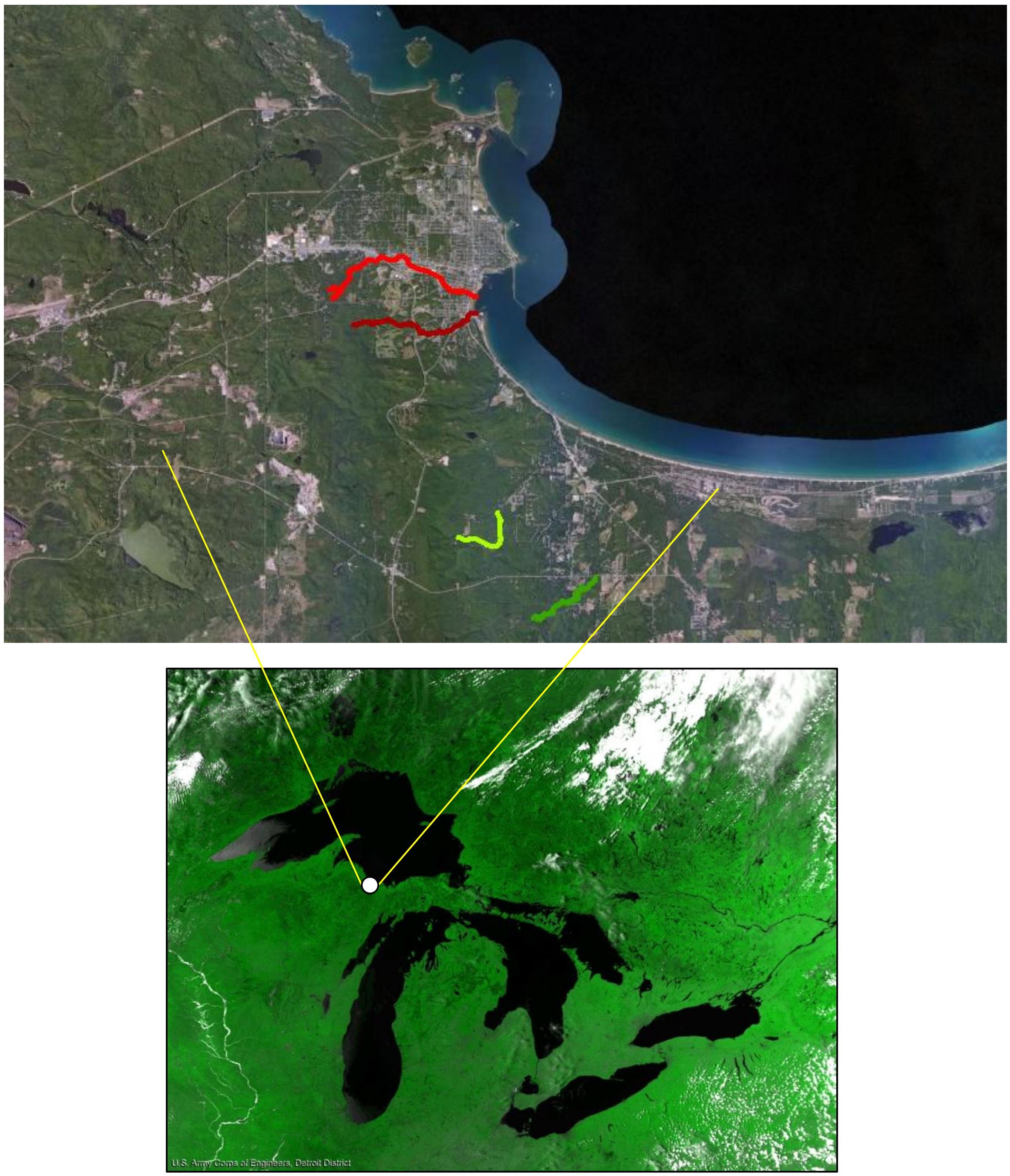

Figure 2.1 Map showing the study sites along Lake Superior, in Marquette, MI. Streams from North to South are: Whetstone Brook, Orianna Creek, Silver Creek, and Cedar Creek.

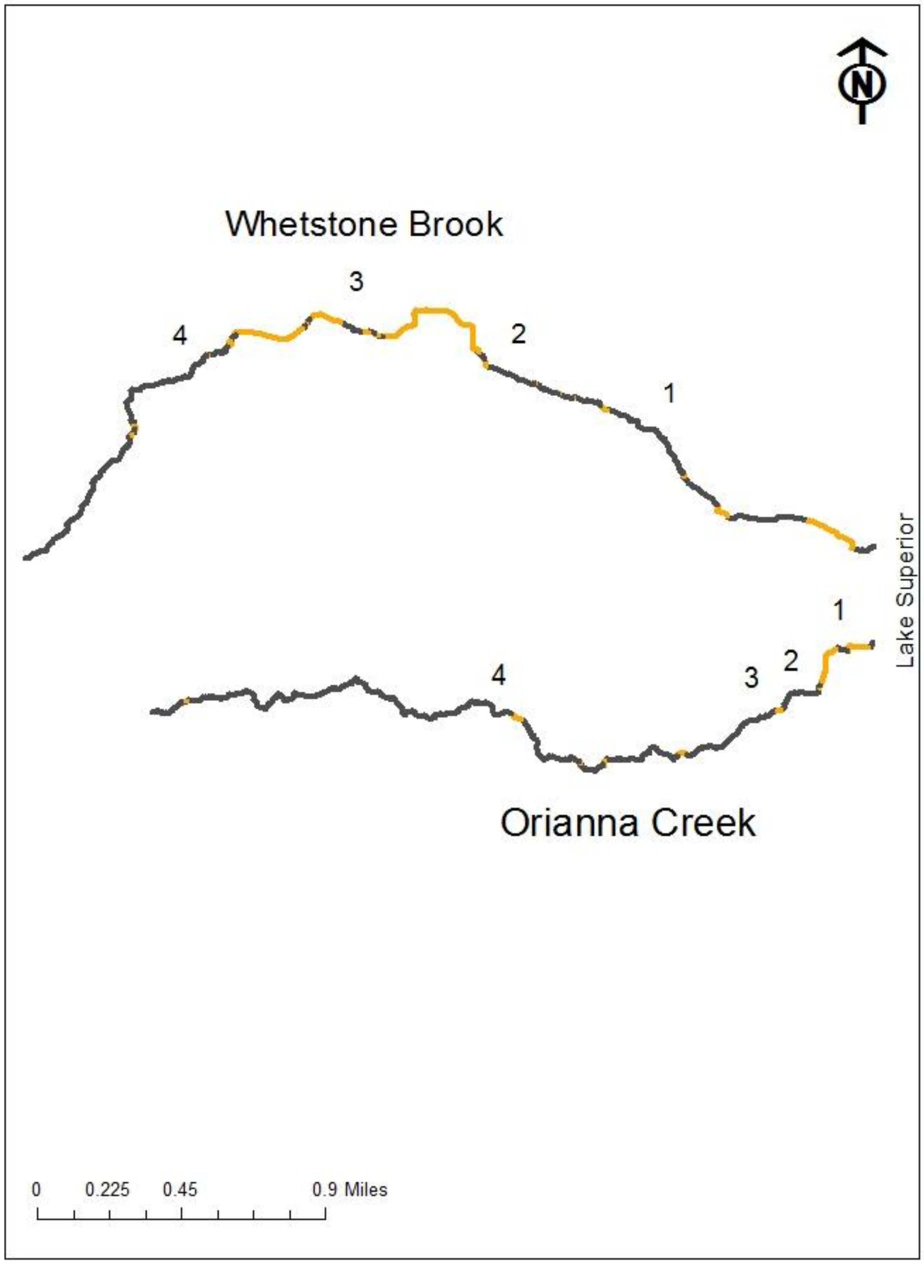

Figure 2.2. Map showing the urban streams along Lake Superior, in Marquette, MI. Both streams are shown from the mouth to the headwater areas. Black coloring represents segments of stream that flow above ground; orange coloring represents culverts where a segment of stream is below ground. Numbers represent stream reaches surveyed in this study.

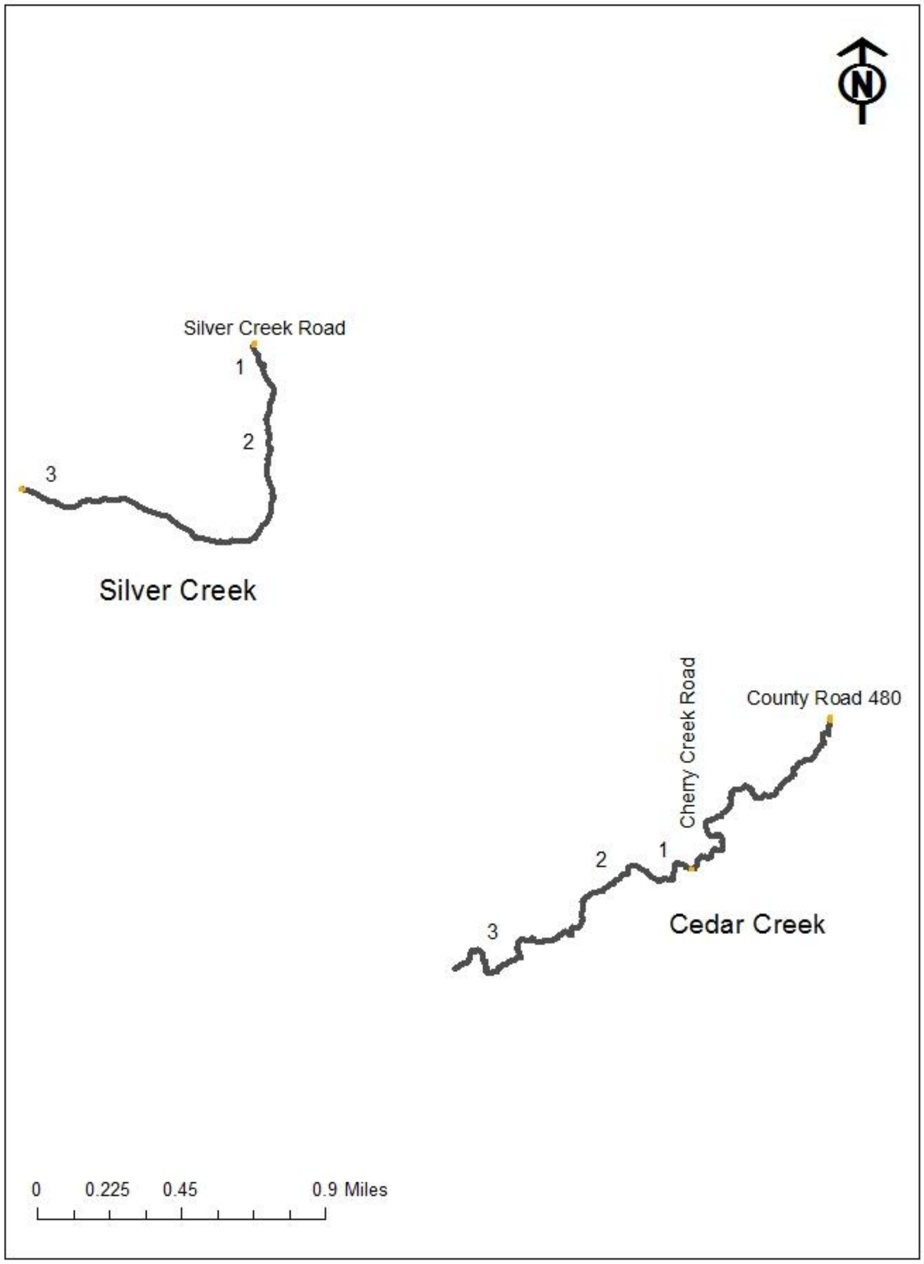

Figure 2.3. Map showing the rural streams in Marquette, MI. Both streams are headwater areas only. Black coloring represents segments of stream that flow above ground; orange coloring represents culverts where a segment of stream is below ground. Numbers represent stream reaches surveyed in this study.

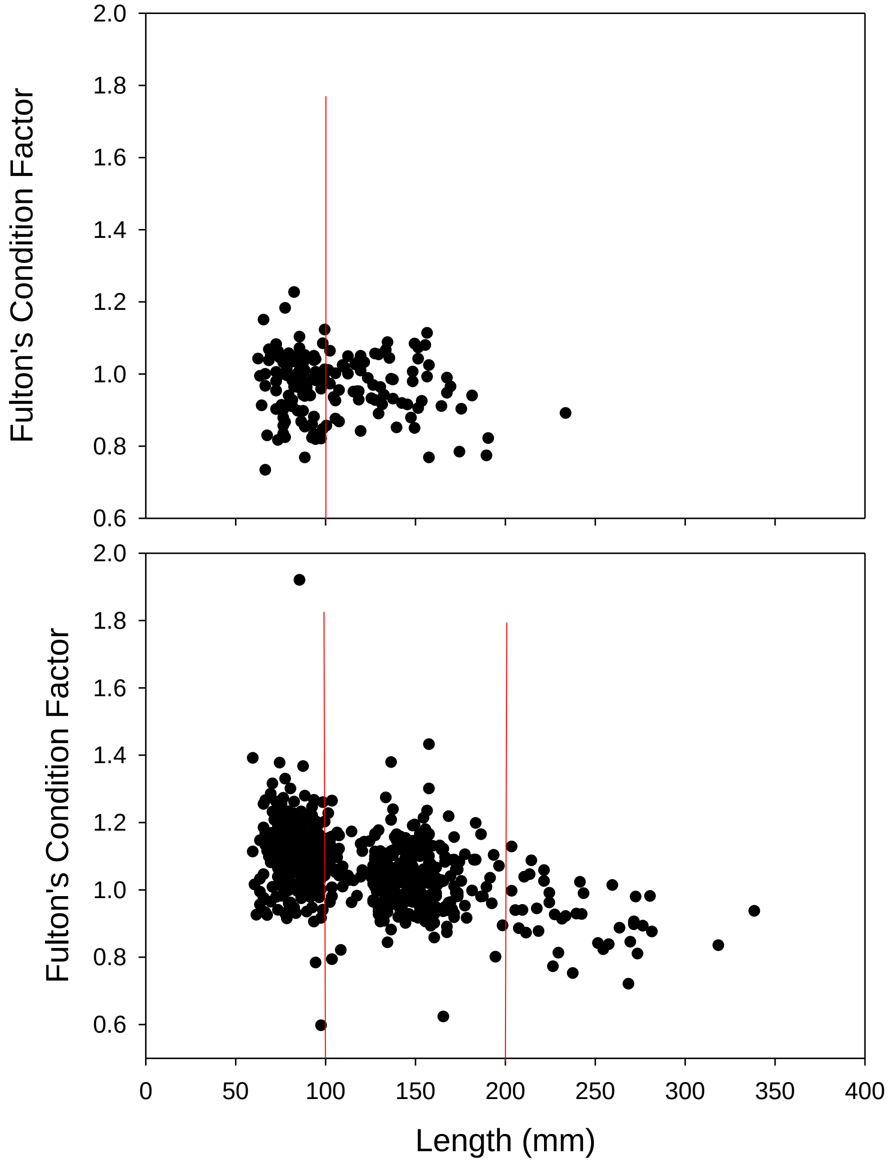

Figure 2.4. Size class determination for Orianna Creek brook trout (top) and Whetstone Brook brown trout (bottom). Brook trout were separated by sub-100 mm and 100+ mm fish using the November 2012 sampling effort in Orianna Creek reach 3. Brown trout were separated by sub-100 mm, 101-199 mm, and 200+ mm fish using the November 2012 sampling effort in Whetstone Brook reach 1.

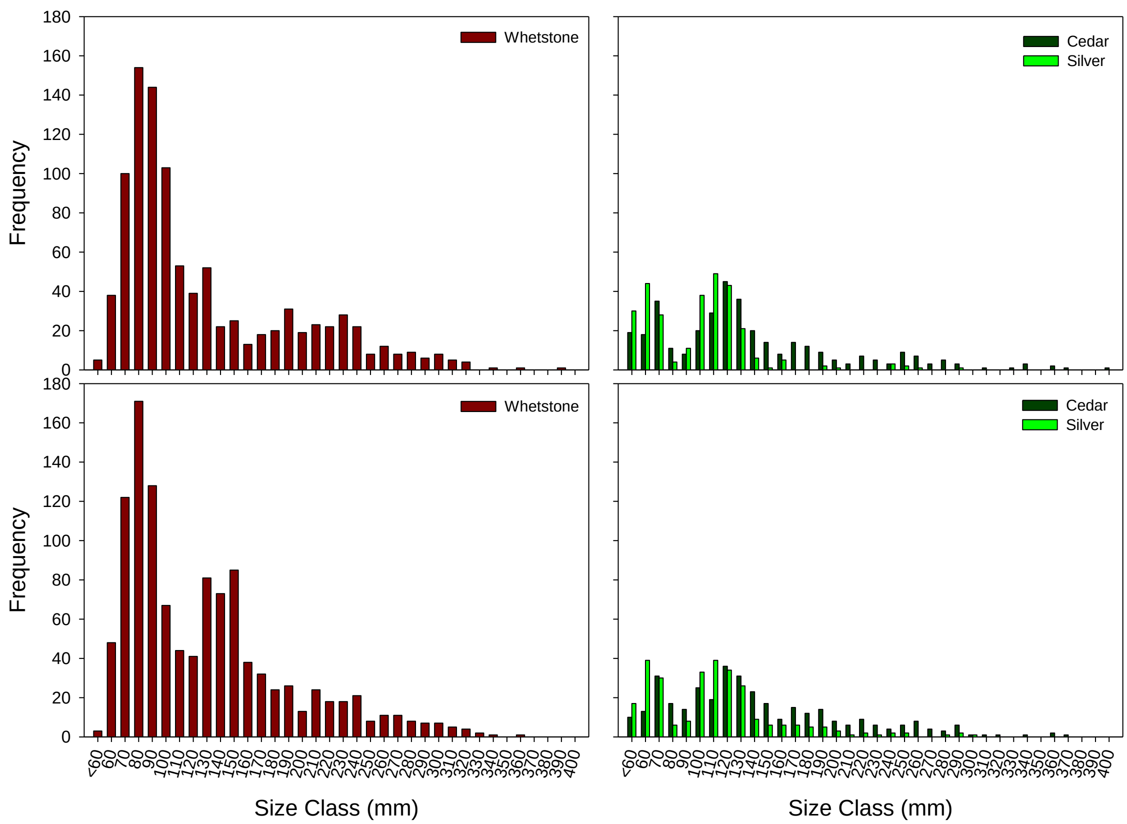

Figure 2.5. Size class frequency of brown trout in urban (left) and rural (right) streams during the winters of 2011-12 (top) and 2012-13 (bottom).

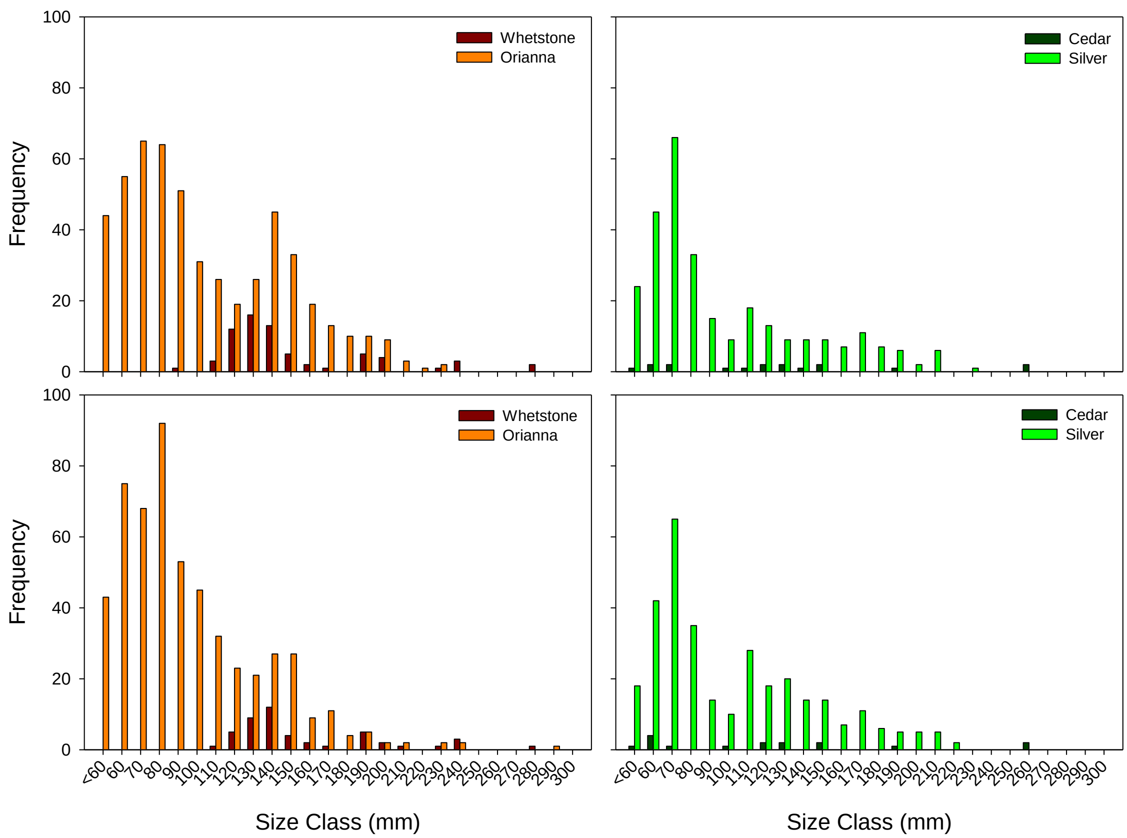

Figure 2.6. Size class frequency of brook trout in urban (left) and rural (right) streams during the winters of 2011-12 (top) and 2012-13 (bottom).

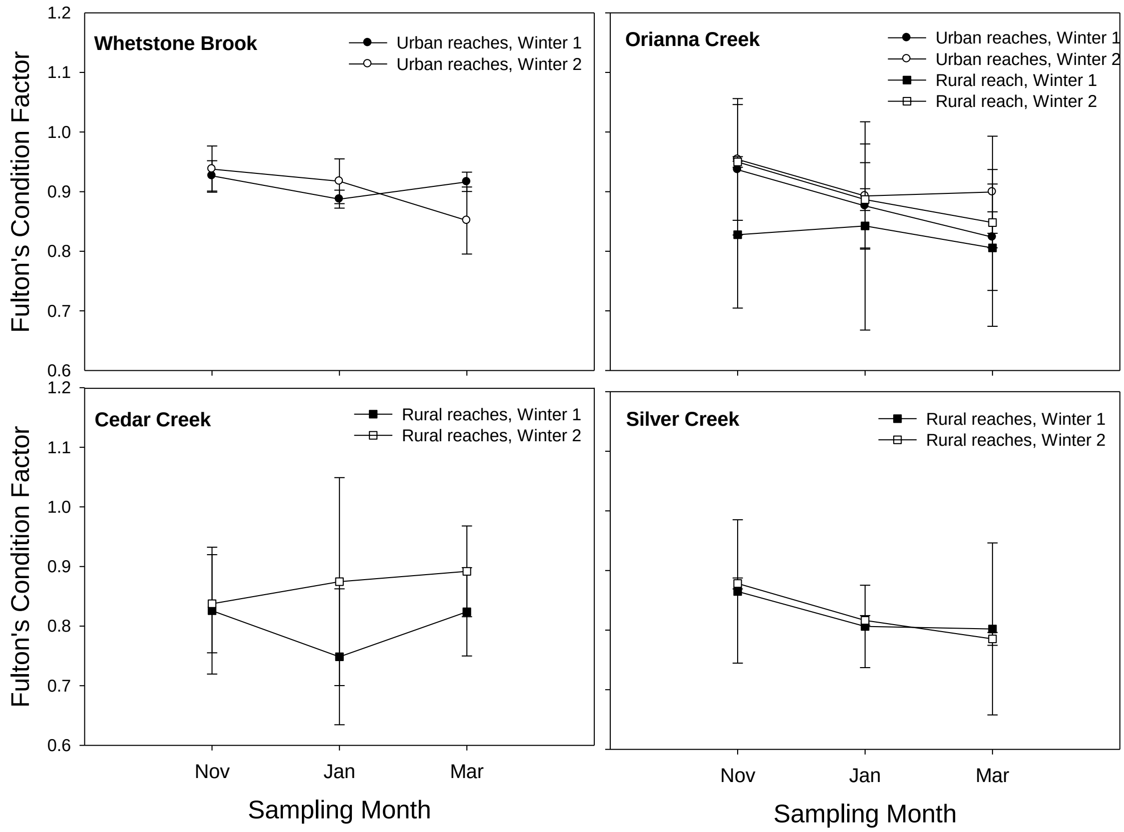

Figure 2.7. Mean fish condition (with standard errors) for brook trout in the urban (top) and rural (bottom) streams. Orianna Creek panel also shows comparisons in fish condition between the urban and rural reaches; significantly higher mean fish condition was shown in the urban reaches during both winters for both sub-100 mm brook trout (winter 1: $P < 0.001$; winter two: $P = 0.033$) and 100+ mm brook trout (winter 1: $P < 0.001$; winter two: $P = 0.035$). Comparisons between urban and rural streams showed significantly higher mean fish condition during both winters in the urban streams for both sub-100 mm brook trout (winter 1: $P < 0.001$; winter two: $P < 0.001$) and 100+ mm brook trout (winter1: $P < 0.001$; winter two: $P < 0.001$).

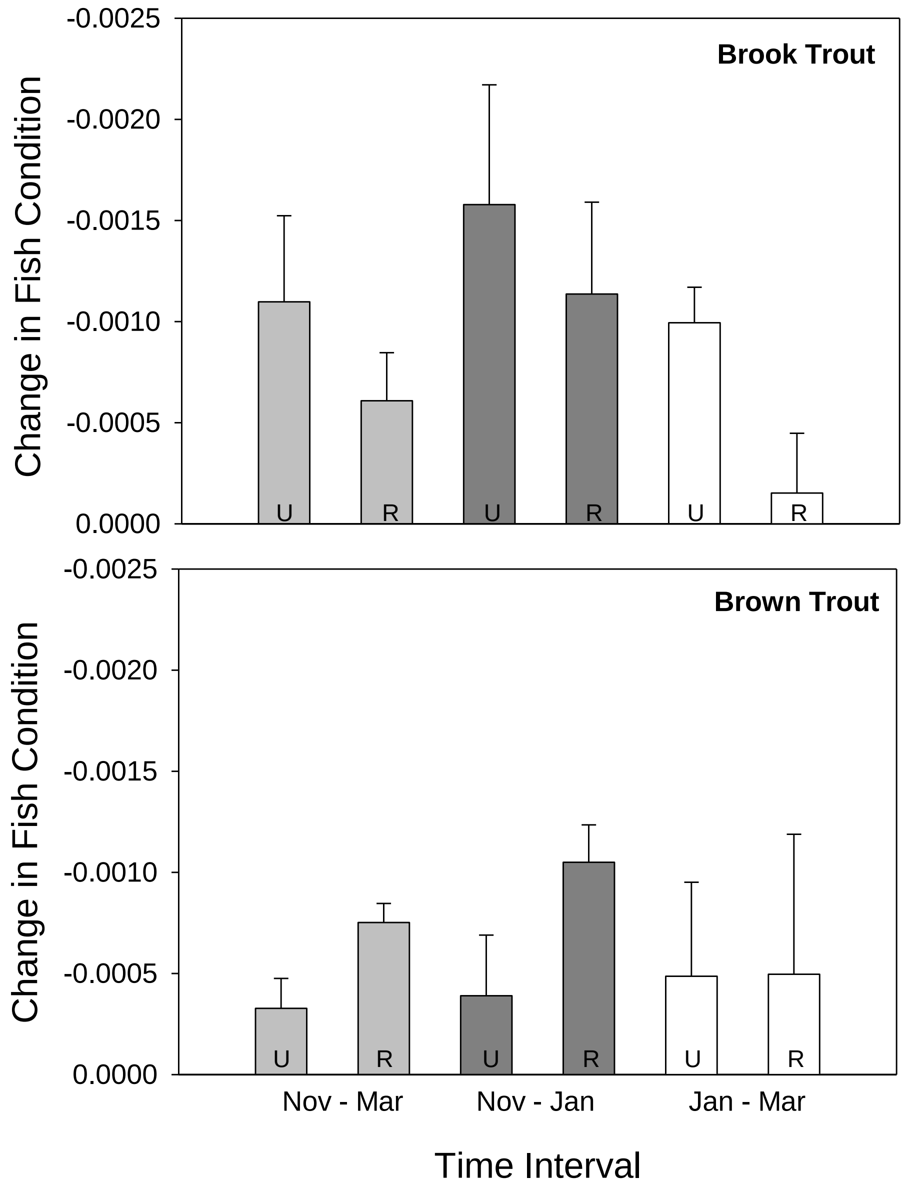

Figure 2.8. Mean change in fish condition (ΔK, with standard errors) for urban (U, left bars) and rural streams (R, right bars) over three winter intervals: November - March (light gray bars), November - January (dark gray bars), and January - March (white bars) for brook trout (top) and brown trout (bottom). Due to low sample size, the winter intervals Nov - Jan and Jan - Mar were grouped for data analyses; comparisons between urban and rural streams showing no significant difference in mean ΔK for brook trout during Nov - Mar ($P = 0.353$) or Nov - Jan / Jan - Mar ($P = 0.169$). For brown trout, a significantly higher mean ΔK was shown in the rural streams for both winter intervals Nov - Mar ($P = 0.008$) and Nov - Jan / Jan - Mar ($P = 0.024$).

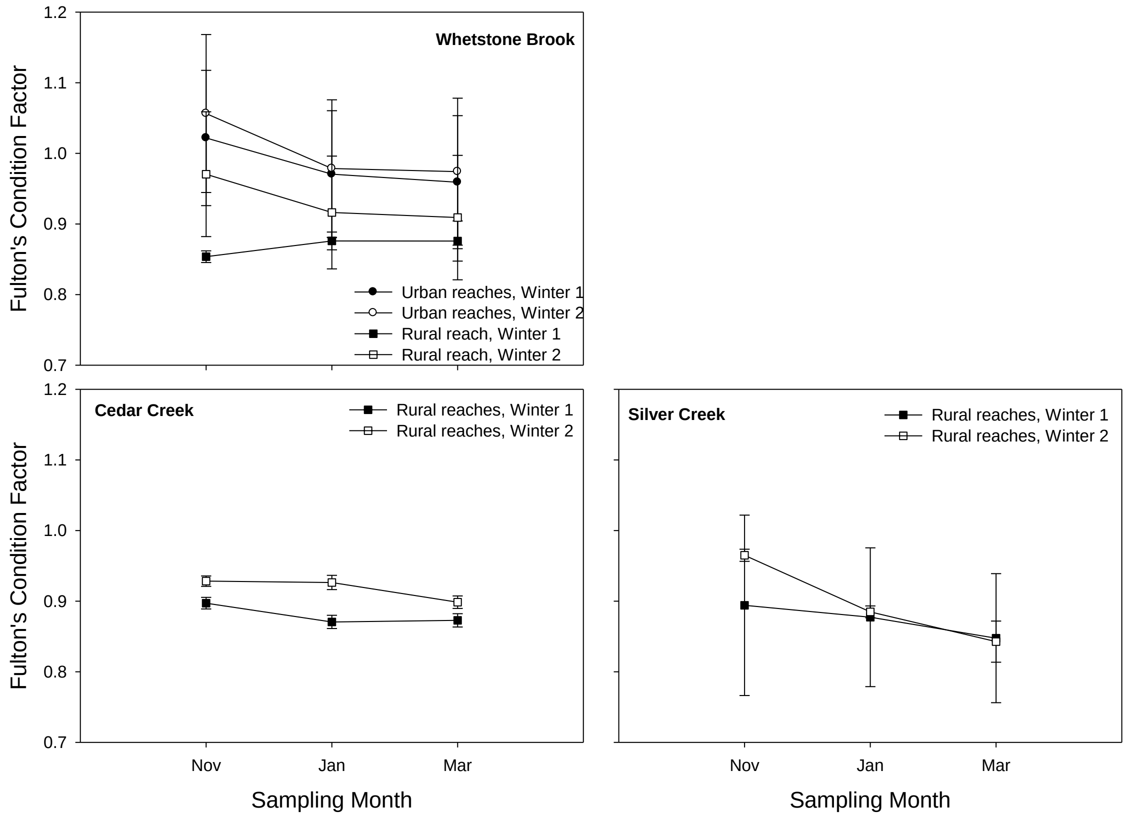

Figure 2.9. Mean fish condition (with standard errors) for brown trout in the urban (top) and rural (bottom) streams. Whetstone Brook panel also shows the difference in fish condition between the urban and rural reaches; significantly higher mean fish condition was shown in the urban reaches during both winters for both sub-100 mm brown trout (winter 1: $P < 0.001$; winter two: $P < 0.001$) and 101-199 mm brown trout (winter 1: $P < 0.001$; winter two: $P < 0.001$). Mean fish condition was also significantly higher for 200+ mm brown trout in the urban reaches during winter one ($P = 0.007$), but not winter two. Comparisons between urban and rural streams showed significantly higher mean fish condition during both winters in the urban streams for both sub-100 mm brown trout (winter 1: $P < 0.001$; winter two: $P < 0.001$) and 101-199 mm brown trout (winter1: $P < 0.001$; winter two: $P < 0.001$). Mean fish condition was also significantly higher in the urban streams for 200+ mm brown trout during winter one ($P < 0.001$), but not winter two.

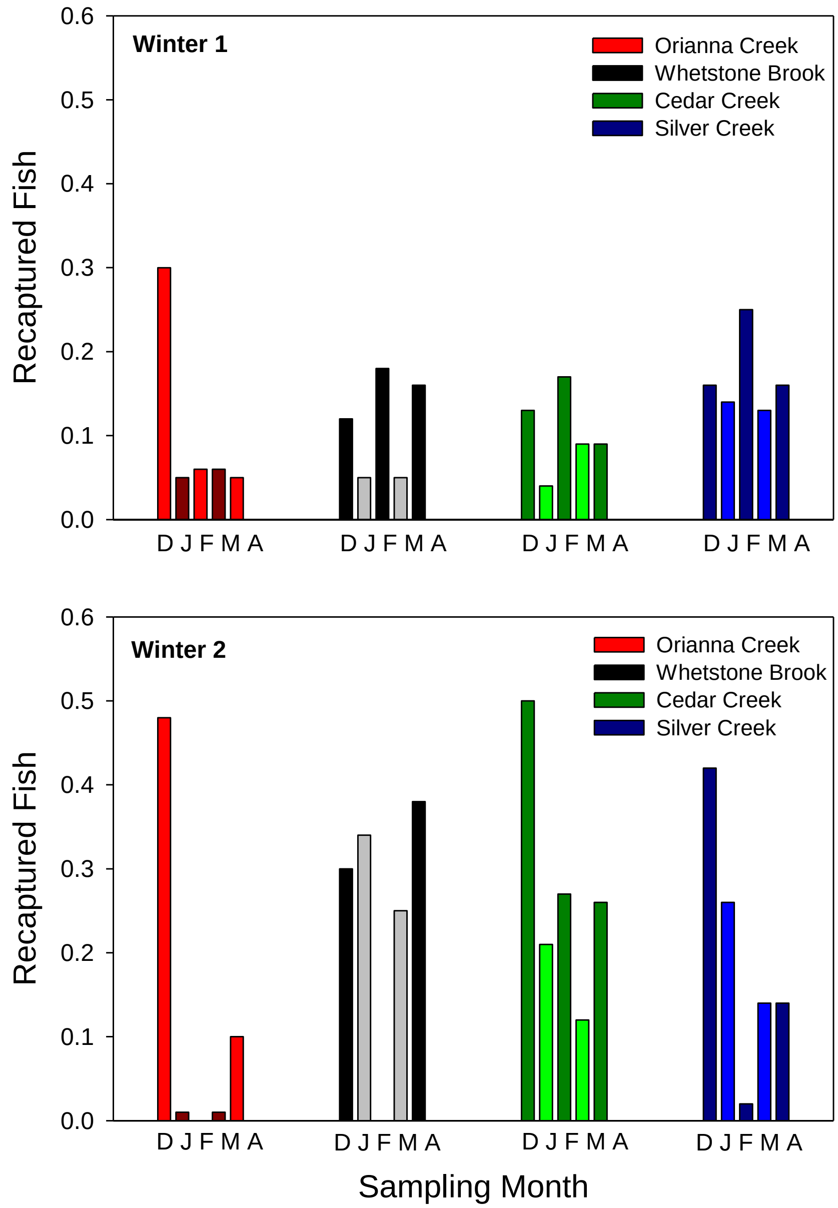

Figure 2.10. Proportion of recaptured brook and brown trout, for each sampling month, via electrofishing (D, F, A) and wanding (J, M) in the urban and rural streams during 2011-12 (top) and 2012-13 (bottom). Mean proportion of recaptured fish was not significantly different between the urban and rural streams ($P = 0.180$), electrofishing and wanding sampling efforts ($P = 0.084$), or winters ($P = 0.133$). D=December, J=January, F=February, M=March, A=April.

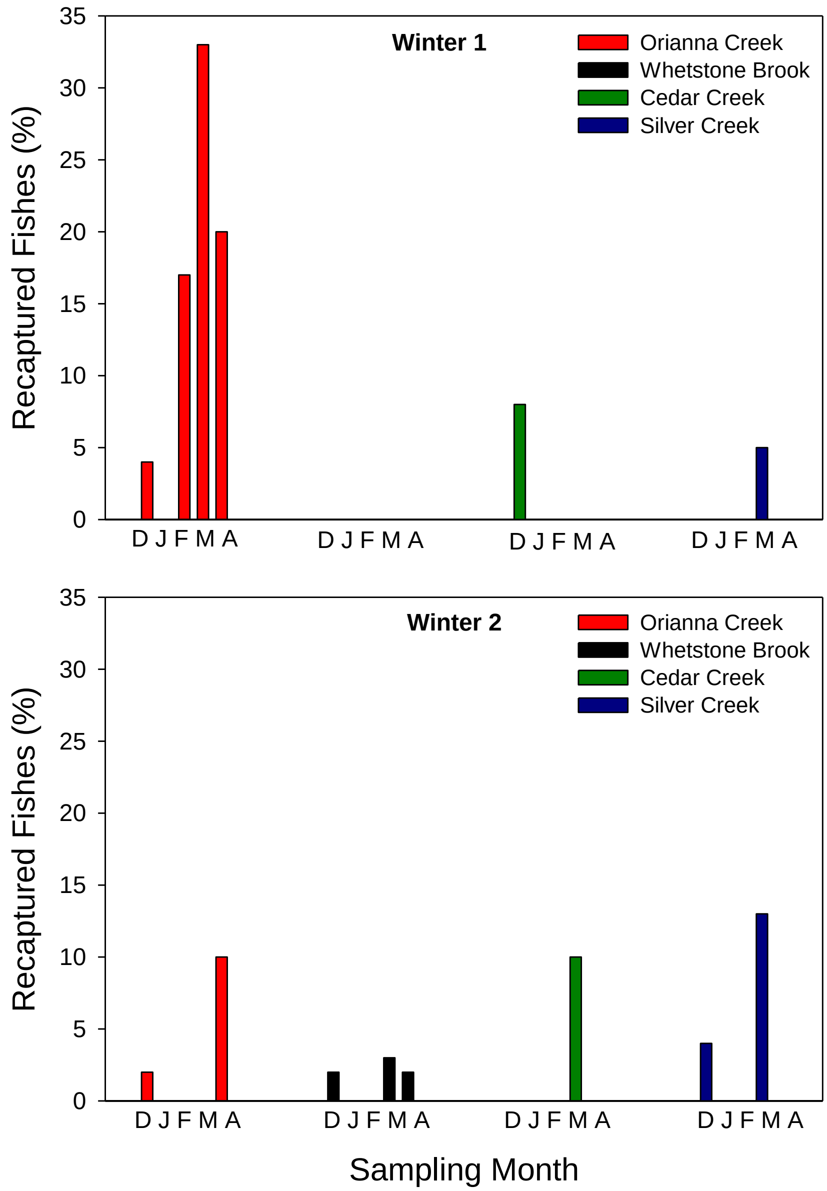

Figure 2.11. Percentage of recaptured brook and brown trout that moved to a reach different than original tagging reach, for each sampling month, via electrofishing and wanding in the urban and rural streams during 2011-12 (top) and 2012-13 (bottom). Mean percentage of recaptured fish that showed movement was not significantly different between the urban and rural streams ($P = 0.253$), capture / sampling type ($P = 0.910$), or between winters ($P = 0.874$). D=December, J=January, F=February, M=March, A=April.

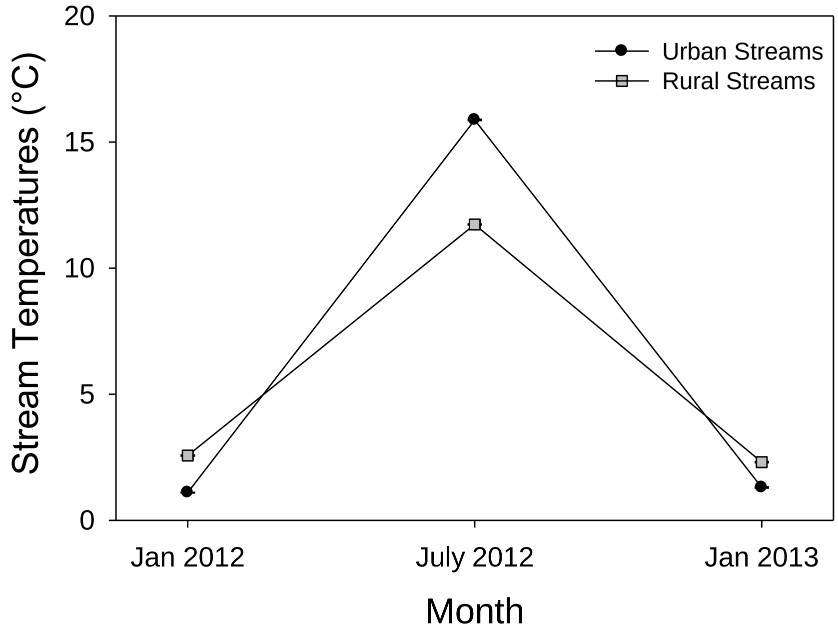

Figure 2.12. Comparisons between mean January 2012, July 2012, and January 2013 temperatures (with standard errors) in the urban and rural streams. A significantly higher mean monthly stream temperature was shown in the rural streams during both winters ($P < 0.001$).

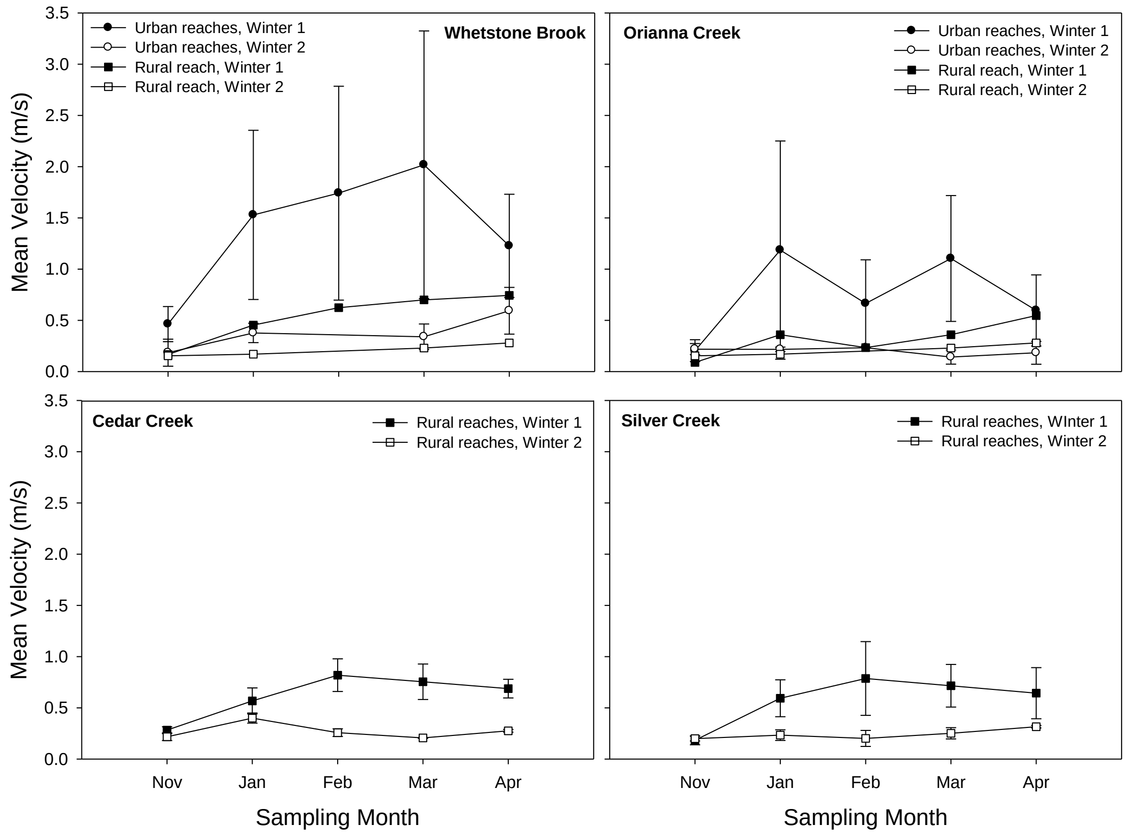

Figure 2.13. Mean water velocity (with standard errors) in the urban (top) and rural (bottom) streams. Whetstone Brook and Orianna Creek panels also show the difference in mean water velocity between the urban and rural reaches; in Whetstone Brook, no difference was shown for mean monthly water velocity (P = 0.076), but significantly higher velocity in the urban reaches was shown in Orianna Creek (P = 0.019). No significant difference between stream types was shown for mean water velocity (P = 0.096).

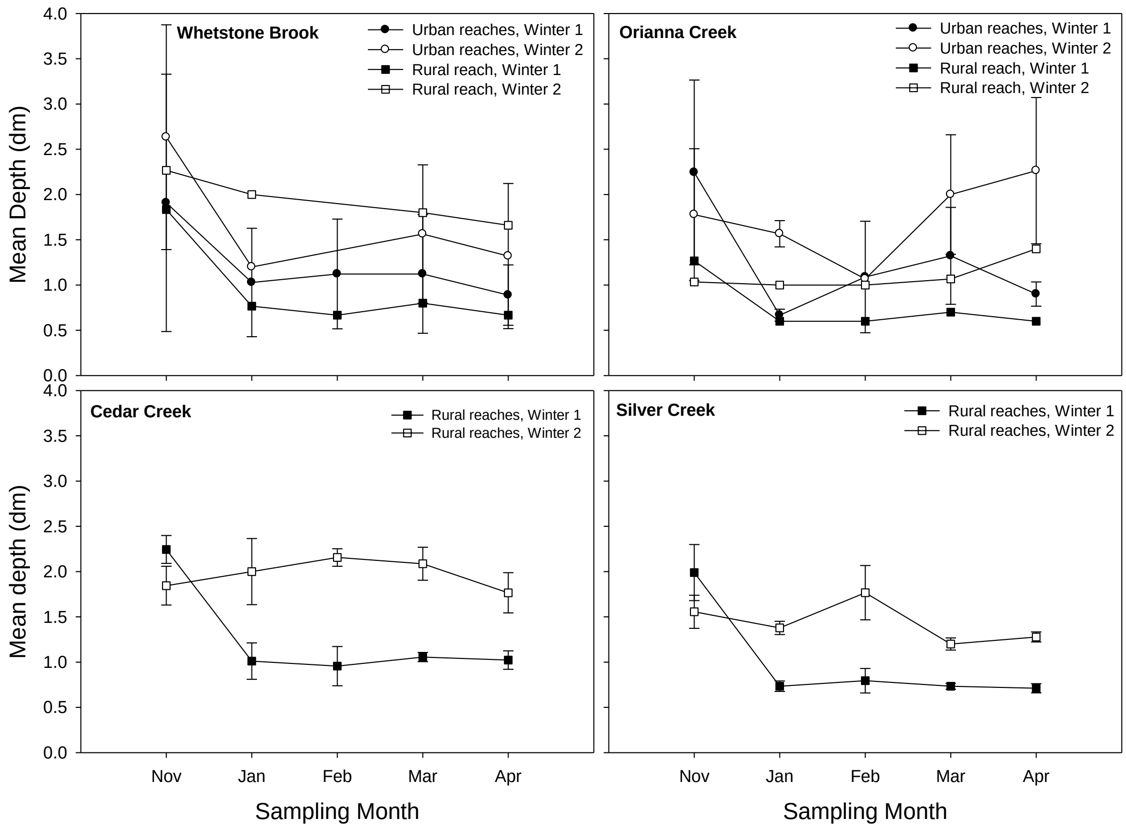

Figure 2.14. Mean water depth (with standard errors) in the urban (top) and rural (bottom) streams. Whetstone Brook and Orianna Creek panels also show the difference in mean water depth between the urban and rural reaches. In Whetstone Brook, no difference was shown for mean monthly water depth (P = 0.756) but significantly higher depth in the urban reaches was shown in Orianna Creek (P = 0.012). No significant difference between stream types was shown for mean water depth (P = 0.813).

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APPENDIX A

Background on Whetstone Brook and Orianna Creek

The watersheds of Whetstone Brook and Orianna Creek comprise 561 and 744 hectares (Marquette Township Planning Commission 2002). These watersheds share similar characteristics; both contain cold water fish communities and drain into Lake Superior, their headwaters are located in undeveloped forested land with steep terrain and wetlands fed by groundwater discharge, and the lower reaches are intensely developed and show signs of degradation.

Whetstone Brook, a second order stream, includes the main stem and several unnamed tributaries. Land use within the watershed is comprised of 13% commercial/industrial, 20% residential, 8% conservation/recreation, 1% institutional/community, and 58% open space/undeveloped (Marquette Township Planning Commission 2002). As a result of city development, many sections have been channelized, routed through culverts, and re-routed under parking lots and roads. Orianna Creek, a third order stream, includes the main stem, Westren Brook, Billy Butcher Creek, and other tributaries. This creek is more ‘natural’ than Whetstone Brook, but its lower reaches also flow through heavily developed areas. Land use within the watershed includes 1% commercial/industrial, 21% residential, 4% conservation/recreation, 2% institutional/community, and 72% open space/undeveloped (Marquette Township Planning Commission 2002).

The headwaters of Whetstone Brook are located upstream of Vandenboom Road (Marquette Township) on minimally developed, forested lands and are characterized by numerous groundwater seeps and wetland areas. A manmade impoundment of less than two acres exists on one of the headwater tributaries. From Vandenboom Road, the stream travels above ground for 152 meters before being re-routed underground below the old Marquette Mall. It resurfaces before and after routing under Highway 41 and then again is re-routed underground behind ShopKo and McClellan Avenue, resurfacing in a small wetland area next to McDonalds. There is virtually no natural riparian habitat in this area; most exposed stream sections flow through maintained lawn areas, pavement, or roadsides. Whetstone Brook flows along Baraga Avenue, through several culverts on industrial land, underneath and along US 41, until it drops down a 3.7 meter long culvert (a fish barrier) below the roundabout on Front Street/US 41 and enters Lake Superior at Founder's Landing (personal communication, Compton, Marquette Hydrology Engineer, City of Marquette). A detention basin exists downstream of where the stream flows below Baraga Street. Collected storm water is detained for a period of time and slowly released into Whetstone Brook via an outlet pipe.

The headwaters of Orianna Creek are located upstream of McClellan Avenue/County Road 553 and this region is characterized by undeveloped forested lands, steep ravines, bedrock outcroppings, and numerous groundwater seeps (Marquette Township Planning Commission 2002). A manmade dam forms a small impoundment used as an irrigation source for the Marquette Golf and Country Club (Marquette Township Planning Commission 2002). Several two track crossings directly enter the stream in this area. From McClellan Avenue, the creek flows along Pioneer Street to

Altamont Street. The majority of the riparian habitat in this area is wetland. Shade and bank stabilization is provided in this area. Orianna Creek then flows through a wooded corridor and crosses under Division Street. From there, the corridor narrows and disappears as the stream approaches the US 41 highway. It is routed through a 183 meter long culvert below the highway and a 114 meter long culvert below the old Soo Line Railroad (a fish barrier), where it emerges and enters Lake Superior adjacent to Shiras Generating Plant.

Numerous point source discharges have been noted along both Whetstone Brook and Orianna Creek (Marquette Township Planning Commission 2002). The storm sewer system of Marquette, Michigan, discharges directly into both watersheds (personal communication, Compton, Marquette Hydrology Engineer, City of Marquette). This discharge can pollute the streams and increase their temperature. Residential areas add road salt, car fluids, such as oil, gasoline, and antifreeze, fertilizers, pesticides, and household supplies. A review of federal and state databases of hazardous materials was conducted in 1997 to assess the magnitude of the risk associated with commercial and industrial land use within 500 feet of both watersheds to identify problem areas (Marquette Township Planning Commission 2002). Whetstone Brook had seven sites of concern, including leaking underground storage tanks, with a potential to water quality impairment associated with possible spills or leaks (Marquette Township Planning Commission 2002). This assessment warranted a serious watershed management issue. Fish kills have been documented in the past; 62 trout were killed in 1967 and 1994 from unknown causes (Marquette Township Planning Commission 2002). Orianna Creek had eight sites of concern, including leaking underground storage tanks, and is listed as a potential concern for watershed management (Marquette Township Planning Commission 2002). An inactive and unlined landfill, with unknown contents, owned by the City of Marquette is discharging groundwater, containing iron hydroxide, and has exposed refuse within Westren Brook (Marquette Township Planning Commission 2002). With the exception of the landfill, the lower reaches have the greatest potential for water quality impairment (Marquette Township Planning Commission 2002).

APPENDIX B

IACUC Approval

Northern Michigan University

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MEMORANDUM

October 31, 2011

TO: Dr. Jill Leonard
Department of Biology

FROM: Terrance Seethoff, Ph.D. TS
Dean of Graduate Studies & Research

RE: **Application to use Vertebrate Animals**
MODIFICATION: Application # IACUC 185
Approval Period: 10/05/2011-04/30/2013

The Institutional Animal Care and Use Committee, has approved your modification to update the personnel for the research: "Habitat Fragmentation Effects on Overwintering Brook and Brown Trout: Fish Condition and Movement".

If you have any questions, please contact me.

kjm